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THESIS

A METHODOLOGY FOR MULTIDISCIPLINARY DECISION MAKING FOR A SURFACE COMBATANT MAIN ENGINE SELECTION PROBLEM

by

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In the ship design process, delivering optimum performance while reducing development and construction costs are key considerations. A great amount of optimization effort should be done before progressing on a project. When it comes to the main engine selection phase that corresponds to the "heart" of the ship, the ultimate choice will affect the overall platform. However, the problem of main engine selection is, as is the overall ship design problem in general, basically a multidisciplinary and multicriterion optimization problem. In this project, we will focus on the multicriterion decision- making methodology for a surface combatant main engine selection problem. This study will consist of a collection of systematic approaches to the overall design optimization. The factors that need to be taken into consideration while selecting a main engine for a surface combatant will be discussed. We propose to develop and examine a mathematical model to analyze the main engine selection problem. The mathematical model will be comprehensively formulated, including both quantitative criteria as well as fuzzy systems, to establish an algorithm that will be able to create a unique solution or a set of Pareto solutions to the main engine selection problem.

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A METHODOLOGY FOR MULTIDISCIPLINARY DECISION MAKING FOR A SURFACE COMBATANT MAIN ENGINE SELECTION PROBLEM

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ABSTRACT

In the ship design process, delivering optimum performance while reducing development and construction costs are key considerations. A great amount of optimization effort should be done before progressing on a project. When it comes to the main engine selection phase that corresponds to the “heart” of the ship, the ultimate choice will affect the overall platform. However, the problem of main engine selection is, as is the overall ship design problem in general, basically a multidisciplinary and multicriterion optimization problem. In this project, we will focus on the multicriterion decision-making methodology for a surface combatant main engine selection problem. This study will consist of a collection of systematic approaches to the overall design optimization. The factors that need to be taken into consideration while selecting a main engine for a surface combatant will be discussed. We propose to develop and examine a mathematical model to analyze the main engine selection problem. The mathematical model will be comprehensively formulated, including both quantitative criteria as well as fuzzy systems, to establish an algorithm that will be able to create a unique solution or a set of Pareto solutions to the main engine selection problem.

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LIST OF ACRONYMS AND ABBREVIATIONS

CODAD	combined diesel and diesel
CODAG	combined diesel and gas
CODOG	combined diesel or gas
COGAG	combined gas and gas
CONAG	combined nuclear and gas
CONAS	combined nuclear and steam
EHP	effective horsepower
GT	gas turbine
HSSL	high speed sea lift
IR	infrared signature
LBP	length between perpendiculars
LOA	length overall
LT	long ton
MTBF	mean time between failure
MTTR	mean time to repair
NMPH	nautical miles per hour
ONR	Office of Naval Research
OPC	overall propulsive coefficient
RS	repairable at sea
SFC	specific fuel consumption
SHP	shaft horsepower

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I. INTRODUCTION

A. MOTIVATION

In the ship building industry, specifically while proceeding in a naval combatant design project, decisions have to be made throughout both the project and the manufacturing phase on financing, management, strategic planning, physical components assembly, and several other contributions to the overall process. Moreover, the design of naval ships is a complex and iterative process. For naval ships, one of the major systems that have significant impact on the ship design is the propulsion plant, which has to be selected early in the design process. The ship design process also involves defining the requirements and constraints, and applying selected design standards to meet those requirements. Thus, a parametric method for characterizing the design space of a navy ship should be implemented as early as possible to obtain adequate parameters enabling a basic decision about the propulsion plant. In other words, there is an obvious need for a rapid and reliable tool for determining a propulsion plant and whether a proposed design is worth pursuing.

B. BACKGROUND AND LITERATURE REVIEW

Multidisciplinary decision making for a surface combatant main engine selection problem is a complex and iterative process. The term “design spiral” [1] can be used to describe the iterative nature of this process cycle. Furthermore, several tradeoff studies must be done to maintain a balance among the design requirements both technically and economically. The tradeoff study should result in the optimum solution given the constraints in the requirements statement of the desired ship.

There have been many approaches and methods demonstrated in [1]–[6] for selecting naval propulsion plants for a prototype ship which has been designed or thought to have been designed for a specific purpose or for several purposes. Moreover, the dynamics of the current and future naval industry environment should be considered in light of emerging technologies. The evolving ship design technologies should lead to potentially promising propulsion plant systems that will efficiently accommodate future naval ship designs. It is obvious that both the future navy ship design concepts and the propulsion plant technologies will have significant performance and economic impacts on the naval ship design industry.

One of the purposes of this thesis is to determine which of the approaches has the most reliable and practical methodology to reveal a satisfactory outcome in the universe of ship design concepts. Several researches have been done, as demonstrated in [1] and [6], for determining the proper propulsion plant for a specific type of ship that has previously defined parameters, such as displacement, speed, range, etc. For those design analyses which have constraints as mentioned in the previous statement, the approach would be limited to those predefined variables which simplify the overall process, as will be reviewed in the next paragraph.

A program study [6], designated High Speed Sea Lift (HSSL), which explored the feasibility of high speed military sealift, was conducted in 2005–2006 by Alion Science and Technology under contract to the U.S. Navy's Office of Naval Research (ONR). The previously defined requirements of the proposed ship, including payload, speed and range, were arbitrarily chosen. The goal of the ONR was to accomplish the mission with a predefined length and displacement. The overall purpose of this analysis was to find a recurring theme for attaining the predefined displacement, or at least to see how close to it they could get. A parametric methodology was developed to attain the HSSL with the desired level of performance. In this analysis, a parametric framework was created which included lift to drag ratio (L/D), propulsive efficiency (η_p), specific fuel consumption (SFC), weight of power, and weight of cargo carrying capacity. By manipulating the parametric framework, the entire mission could be described using the three parameters of payload, speed, and range, which could then be elaborated by implementing several other input parameters.

In this thesis we will conduct a similar approach by establishing a parametric framework, which can eventually result in a prediction of how much power might be needed to move a naval ship that meets initially defined requirements.

C. THESIS OVERVIEW

The objectives of this thesis are as follows:

Initially, we want to gather data from a handful of widely different navy ship types to create an observed frontier or an apparent state-of-the-art view. The data will present a baseline parametric framework which will then be used to create desired trend lines. We want to analyze the parameters of primary importance in the analysis of the data we gathered to set a prediction concept. Thus, we want to tabulate and manipulate the data that we will use later in the analysis. It should be emphasized that the primary algorithm and the methodology developed in this thesis are not restricted to the data utilized to demonstrate its applicability and can be easily modified and applied to a different set of data should one become available.

Second, we want to define the factors that need to be taken into consideration while selecting a main engine for a navy ship. The factors of primary importance in the analysis will then lead us to attain a prediction of how much power might be needed for the desired ship. We want to propose a mathematical model to analyze the main engine selection problem. Eventually, the results of the mathematical model will be used to attain an algorithm which will provide the prediction of a propulsion plant choice regarding the desired requirements. Such an algorithm, if it can be derived, will be very useful in preliminary ship design phases. During subsequent phases in the ship design process, more elaborate algorithms can be used to refine the results.

This thesis is organized as follows:

Chapter II contains the factors affecting the main engine selection problem, not only for navy ships but also for a broad variety type of ships in general. In this chapter, we present an overview of the equations for a marine vehicle which will eventually contribute to the propulsion plant selection process. We also define a few coefficients which will be used to establish trend lines to predict the desired data of the navy ship.

In Chapter III, the data representing a handful of widely different navy ship types are presented to establish the main engine selection criteria. A mathematical model is developed with respect to the data and corresponding criteria presented in Chapter II. By establishing a parametric method for characterizing the design space, we keep track of two different approaches to predict the propulsion plant characteristics. The first one is referred to as the Admiralty Coefficient "Best Practices Curve" [6], and the second one is referred to as the "Lift to Drag Ratio (L/D) Best Practices Curve" [6]. Although they use different types of analysis, both provide a preliminary prediction of how much power might be needed to move a given navy ship.

Chapter IV presents a multicriterion design optimization to establish a reasonably converged prediction of propulsion plant characteristics corresponding to the given navy ship requirements. This is achieved by examining main propulsion system options in state of the art along with the constraints to consider when deciding on a propulsion system. Both technical and non-technical aspects affecting the decision process are investigated to obtain an objective judgment in the preliminary ship design.

In Chapter V, an algorithm is derived by using the optimized data points from the "Best Practices Curve" [6] analyses for desired input parameters of the given ship requirements. For any desired ship type with its predefined requirements, we will be able to predict the optimum propulsion plant characteristics to determine how much power might be needed to move that ship.

Chapter V summarizes the conclusions and gives recommendations for future research.

II. MAIN ENGINE SELECTION CRITERIA

There are many aspects that affect the main propulsion plant selection of a naval combatant. For instance, to find the resistance components of the ship related to optimized ship hull dimensions, we may calculate the total resistance value which will be used to determine the effective horsepower (EHP). To determine an optimal prime mover for the candidate ship, shaft horsepower (SHP) is needed whose formula is derived by EHP. Several analyses like this example allow an optimum propulsion plant selection that would provide desired speed and would accord with the hull design as well as several other criteria necessary for the prototype ship's mission.

We will examine the different aspects that need to be considered when choosing a main engine for a navy ship. The criteria for selecting a main engine may differ from ship to ship and the results of the decision phase are governed by the requirements. The importance of each criterion will also change. However, there are a few general aspects that remain the same for almost all types of ships, and we will briefly define them here.

A. THE QUANTITATIVE CRITERIA, PARAMETERS

The quantitative criteria include: overall dimensions, draft, hull design, weight, horsepower, required speed, required endurance range, and ship resistance (drag).

Draft (T)

Draft is the vertical distance between the waterline and the deepest part of the ship at any point along the length. Drafts are typically measured to the keel, which are given as draft forward (T_f), draft aft (T_a), and mean draft (T) or (T_m) [7], [8].

Length Overall (LOA)

Length overall (LOA) is the maximum length of the ship, including any extensions beyond the perpendiculars [7], [8]. Although the length between perpendiculars (LBP) is used for the calculation of hydrostatic properties, we will use LOA instead due to the availability of the navy ship data for this analysis.

Beam (B)

Beam or breadth is the width of the ship. Maximum beam is the width at the widest part of the ship, which is typically placed around the mid ship [7], [8].

***Displacement* (Δ)**

For a ship in static equilibrium, displacement (Δ) is equal to the weight of the ship measured in long tons (LT) of 2,240 pounds [7], [8]. Displacement is usually given for either the lightship, which is the weight of the ship without cargo or stores or full-load conditions. A ship's displacement is related to the volume of displaced water (∇) by the weight density of water $(\rho g / g_c)$. In this analysis, displacement is one of the major parameters that govern most of the variables to obtain desired solutions.

$$\Delta = \frac{\nabla \rho g}{g_c} \tag{2.1}$$

Speed (V)

Ship speed is measured in knots (kt) or nautical miles per hour (NMPH), which is also a deterministic parameter for the ship design process. In most ship design analyses, speed is defined early in the process as a predefined requirement.

Total Resistance (R_T)

As a ship moves through the water, it experiences force acting opposite to its direction of motion. This force is the water's resistance to the motion of the ship, which is referred to in [9] as "total resistance" (R_T). This resistance force is used to calculate the ship's effective horsepower (EHP). The total resistance of the ship is also called the Drag (D) of the ship [6].

Shaft Horsepower (SHP)

Shaft horsepower (SHP) is the power delivered to the propeller shafts of a ship by diesel engines, gas turbine engines, steam engines or nuclear power. This is one of the most important parameters that need to be derived early in the design process to determine the propulsion plant characteristics. Shaft horsepower is the quantity that is purchased from the engine manufacturer. In other words, this parameter will be the outcome of our analysis to predict the engine's characteristics.

Effective Horsepower (EHP)

Effective horsepower is defined as the "horsepower required moving the ship's hull at a given speed in the absence of propeller action [9]." The amount of power is determined through the concept of EHP, which can be determined using the following equation:

$$EHP(hp) = \frac{R_T\,(Ibf\,)xV(\,ft/s)}{550(\frac{ft.Ibf}{s.hp})} \tag{2.2}$$

Specific Fuel Consumption (SFC)

Specific fuel consumption is the weight of fuel per unit time per unit power delivered to the propeller [9]. It is expressed in the units of $(lb/hr - hp)$. SFC can be determined using the following equation:

$$SFC = \frac{\dot{m}_f}{SHP(hp)} \tag{2.3}$$

Overall Propulsive Coefficient (OPC)

The overall propulsive coefficient is equal to the ratio between the effective horsepower (EHP), and the total installed shaft horsepower (SHP) delivered by the main engine [6]. OPC can be determined using the following relationship:

$$OPC = \frac{EHP}{SHP} \tag{2.4}$$

B. ADDITIONAL COEFFICIENTS

We will also take advantage of a couple of coefficients, the Admiralty Coefficient (A) and the Volumetric Froude Number (Fn_{vol}), which will provide us with a prediction of the power requirement for the desired ship.

Admiralty Coefficient (A)

The Admiralty coefficient is a constant which is valid for a given ship and is useful when simple ship estimations are needed. The Admiralty coefficient, *A*, is constant for a given hull and gives the approximate relationship between the needed propulsion power, *P*, ship speed, *V* and displacement, Δ. The constant is defined [7] as

$$A = \frac{P}{\Delta^{2/3} V^3} \tag{2.5}$$

Volumetric Froude Number (Fn_{vol})

The Froude number characterizes the ratio of the inertial force and the gravitational force acting on a unit volume of a liquid [6]. Quantitatively, the volumetric Froude number is defined by Equation (2.6) where *V* is the flow velocity or the speed of a ship, *g* is the acceleration of gravity, and ∇ is the volume of displaced water. In the parametric method for characterizing the design space, we will use this parameter to establish parametric curves for both approaches that we will discuss in the next chapter.

$$Fn_{vol} = \frac{V}{\sqrt{g \nabla^{1/3}}} \tag{2.6}$$

In addition to those parameters aforementioned, there are several other criteria, such as reliability, maintainability, complexity, redundancy, maneuvering ability, availability, and manning requirements, which are unmeasurable parameters and will be considered in Section IV.B.2.

III. PARAMETRIC METHOD FOR CHARACTERIZING THE DESIGN SPACE

The main engine selection criteria is based on the data [10] representing a handful of widely different navy ship types, which will be presented in the next section. A mathematical model is developed with respect to the data and corresponding criteria presented in Chapter II. To characterize the design space we will establish the parametric method, including two different approaches to predict the propulsion plant characteristics. The first approach is established by the Admiralty Coefficient "Best Practices Curve" [6], including the Admiralty coefficient versus the volumetric Froude number, and the second approach is based on the "Lift to Drag Ratio (L/D) Best Practices Curve" [6], including the lift to drag ratio versus the volumetric Froude number.

Establishing a parametric method to characterize the design space can be possible by analyzing the background data, utilizing regression analysis, and examining two different approaches which will be reviewed in this section. We expect that both approaches will provide estimate propulsion plant characteristics for a preliminary ship design process.

A. BACKGROUND DATA REPRESENTING VARIOUS NAVY SHIP TYPES

The historical data presented in Table 1 includes several characteristics of various navy ship types, which will be the baseline of our parametric framework to establish the mathematical model.

Name	Type	LOA (ft)	Beam (ft)	Draft (ft)	Light Ship (LT)	Loads (LT)	Full Load (LT)	SHP (hp)	Speed (design) (kts)	Endurance (NM)	Endurance Speed (kts)
Forrest Sherman	DD 931	418.5	45	15	2734	2182	4916	70000	33	4500	20
Spruance	DD 963	563.3	55	20.5	5825,9	1974.1	7800	80000	30	6000	20
Farragut	DLG 6	512.5	52.4	17.9	4167	1481	5648	85000	32	5000	20
Leahy	DLG 16	533	53.4	53.4	5146	2444	7590	85000	32	8000	20
Belknap	DLG 26	547	54.9	18.1	5409	2481	7890	85000	32	7100	20
Dealey	DE 1006	315	36.8	11.1	1314	563	1877	20000	27	6000	12
Claud Jones	DE 1033	312	38	12.11	1314	602.5	1916.5	8700	21.5	7000	12
Bronstein	DE 1037	372	41	23	1791.7	841	2723	20000	26	4000	15
Garcia	DE 1040	414	44	24	2440.8	930.6	3371.4	35000	27	4000	20
Knox	DE 1052	438	47	15	3020.4	4065.9	4065.9	35000	27	4500	20
Brooke	DEG 1	414	44	24	2710	716	3426	35000	27	4000	20
Oliver Hazard Perry	FFG 7	445	47.4	14.4	2647.9	838	3485.9	40000	28.5	4500	20

Table 1. Background Data of Various Navy Ship Types, After [10].

B. REGRESSION ANALYSIS

To establish the parametric method to characterize the design space we need to conduct an optimization and parametric study, which will include two different approaches for predicting the propulsion plant characteristics. The regression analysis [11] is the best approach we can follow for this analysis, because we know which parameter to use and how the method would be most suitable for this prediction. Moreover, regression analysis can be used not only in analysis but also in the design space for resistance calculations, weight estimates, cost estimates, and so on.

Regression analysis is a formalized method which can be used to develop models or equations from historical data as presented in Table 1. When the relationship between the dependent variables is not obvious this technique is used for curve fitting to establish a converged prediction trend.

Furthermore, by conducting the parametric approach, relationships can be estimated using explanatory variables such as weight, displacement, speed, and range which can be used to predict power requirements of a surface combatant. The procedure consists of statistically fitting a curve or function to a set of corresponding historical data as presented in Table 1 and then substituting the appropriate parameter of the new system into the resulting equation by utilizing the regression analysis. Regression analysis that we will conduct for this thesis consists of the following steps:

Assuming Equation Form

To establish a reasonable equation form, we use a scatter diagram to plot the historical data presented in Table 1, which includes several characteristics of various navy ship types in this case. We use the Microsoft Excel 2010 program to create plots and diagrams by logging in the data in Table 1, which we will use to predict the power requirements. According to the results of the plot, the program can derive the corresponding equation of the trend from the data which we will use for predicting the suitable equation form. There are several standard equation forms that we can assume for our analysis as presented in the following [11]:

(1) Linear equation form

$$y = a_0 + a_1 x \tag{3.1}$$

(2) Multiple linear equation form

$$y = a_0 + a_1 x_1 + a_2 x_2 + \ldots \tag{3.2}$$

(3) Hyperbolic equation form

$$y = \frac{1}{a_0 + a_1 x} \rightarrow z = \frac{1}{y} = a_0 + a_1 x \rightarrow (linear) \tag{3.3}$$

(4) Polynomial equation form

$$y = a_0 + a_1 x + a_2 x^2 + \ldots \tag{3.4}$$

(5) Exponential equation form (linear or semi-log)

$$y = ab^x \rightarrow \log y = \log a + x \log b \tag{3.5}$$

(6) Geometric equation form (linear or log-log)

$$y = ax^b \rightarrow \log y = \log a + b \log x \tag{3.6}$$

Transforming the Equation to Linear Form

The linear least squares method that we will discuss under the next topic fits a straight line or a flat plane to a group of data points. Usually the true relationship that wanted to be modeled is curved, rather than flat. For instance, if something is growing exponentially, either increasing or decreasing at a steady rate, the relationship between X and Y is curve rather than a straight line. The linear least squares method can be adapted to fit the data by performing non-linear regression. The new variables can be created from the data which will be the nonlinear functions of the variables in our data. If the new variables are constructed properly, the curved function of the original variables can be expressed as a linear function of our new variables. This is how we transform the equation derived from the data presented in Table 1 to linear form by performing the least squares method for this analysis.

Performing Least Squares to Fit to Data

To find the best-fitting curve to a given set of points, we need to perform a mathematical procedure by minimizing the sum of the squares of the offsets of the points from the curve. Instead of the offset absolute values, the sum of the squares of the offsets is used, because this allows the residuals to be treated as a continuous differentiable quantity. One of the simplest and most commonly applied form of linear regression techniques is the linear least squares fitting, and this method provides a solution to the problem of finding the best fitting straight line through a set of points which we use for our analysis. The following types of lines and curves (see Figures 1 through 6) present several different approaches to this methodology [12] by performing the equation as

$$Y = b_0 + b_1 X^{b_2} \tag{3.7}$$

(7) Increasing at a steady rate

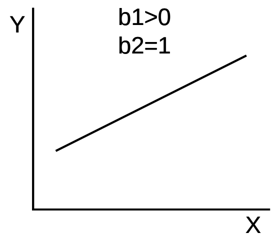

Figure 1. Linear Trend Line Increasing at a Steady Rate, After [11].

(8) Decreasing at a steady rate

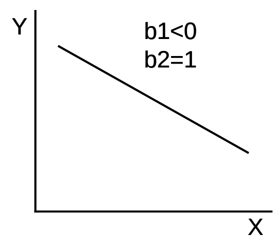

Figure 2. Linear Trend Line Decreasing at a Steady Rate, After [11].

(9) Increasing at a decreasing rate

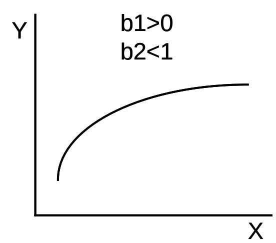

Figure 3. Exponential Trend Increasing at a Decreasing Rate, After [11].

(10) Decreasing at a decreasing rate

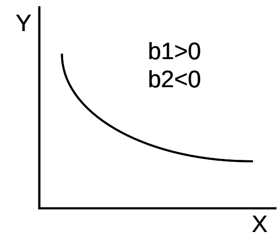

Figure 4. Exponential Trend Decreasing at a Decreasing Rate, After [11].

(11) Increasing at an increasing rate

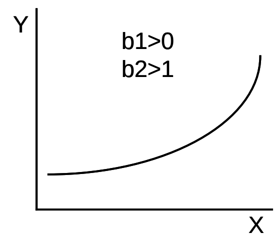

Figure 5. Exponential Trend Increasing at an Increasing Rate, After [11].

(12) Decreasing at an increasing rate

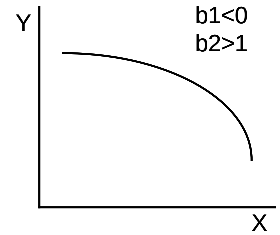

Figure 6. Exponential Trend Decreasing at an Increasing Rate, After [11].

Test for “Goodness of Fit”

A “goodness of fit” test, in general, refers to measuring how well the related data corresponds to the fitted model, which is assumed for this analysis. We will use this concept as a way of checking the model fit to decide the reliability of our approach. For a regression analysis, in essence, the “goodness of fit” test compares the related values to the expected values which are fitted or predicted. “Goodness of Fit” of a linear regression model attempts to assess how well a model fits a given set of data, such as the data presented in Table 1, or how well it will predict a future set of observations as prediction of a power requirement for a desired ship.

C. ADMIRALTY COEFFICIENT “BEST PRACTICES CURVE” APPROACH

As we explained in Chapter II the Admiralty coefficient is a constant which is valid for a given ship and is useful to give approximate relationships between the needed propulsion power, P, ship speed, V, and displacement, Δ. Our goal in this approach is to determine the required propulsion power according to the given ship speed and the displacement. We will conduct a similar approach as stated in [6] by taking advantage of the practicality of the methodology.

Calculations of the Parameters

The first step for the Admiralty Coefficient “Best Practices Curve” approach is to calculate necessary parameters to create a parametric curve. We used the background data representing various navy ship types in Table 1 to calculate the ship drag (D), lift to drag ratio (L/D), Admiralty coefficient (A), specific fuel consumption (SFC), Froude number (Fn), volumetric Froude number (Fn_{vol}), and the effective horsepower (EHP) of the each given ship. The calculations of the parameters presented in Table 2 were established by the Microsoft Excel program via the corresponding equations explained in Chapter II. We will also use some of the calculated parameters for the next approach, which will be discussed under ‘Lift to Drag Ratio (L/D) “Best Practices Curve” Approach’ in the following section. Table 2 presents the calculated parameters with respect to the background data representing various navy ship types listed in Table 1.

Name	Type	Admiralty Coefficient (A)	SFC (lbm/(hp-hr))	Froude Number (Fn)	EHP (hp)	Drag (D) (kN)	Lift/Drag Ratio (L/D)	Volumetric Froude Number (Fn_{vol})
Forrest Sherman	DD 931	0.006737234	1.39403616	0.480049611	42000	1847.187832	26.52549704	1.31680217
Spruance	DD 963	0.007533495	0.6218415	0.376158857	48000	2322.178988	33.47816357	1.108444775
Farragut	DLG 6	0.008179107	0.639446317	0.420651999	51000	2313.107977	24.33668927	1.247697878
Leahy	DLG 16	0.006716471	0.659523464	0.412483221	51000	2313.107977	32.70458066	1.187731447
Belknap	DLG 26	0.006545121	0.754375286	0.407170428	51000	2313.107977	33.99725183	1.180082538
Dealey	DE 1006	0.006677735	1.4364945	0.452718666	12000	645.049719	29.00239062	1.264915822
Claud Jones	DE 1033	0.005673678	1.52946895	0.362227215	5220	352.3771604	54.20805031	1.003757713
Bronstein	DE 1037	0.005835502	1.839465102	0.401163851	12000	669.8593236	40.51601751	1.144829066
Garcia	DE 1040	0.007908666	0.732679992	0.394896702	21000	1128.837008	29.76745863	1.147283171
Knox	DE 1052	0.006980271	2.845479456	0.383925203	21000	1128.837008	35.89948094	1.112020742
Brooke	DEG 1	0.007824414	0.56372112	0.394896702	21000	1128.837008	30.24954419	1.14421537
Oliver Hazard Perry	FFG 7	0.00751592	0.60352341	0.402054353	24000	1222.199468	28.42729586	1.20429887

Table 2. Calculated Parameters for The Admiralty Coefficient "Best Practices Curve" Approach, After [10].

Establishing the Volumetric Froude Number (Fn_{vol}) versus Admiralty Coefficient (A) Curve

To establish an optimum equation form, we created a scatter diagram by plotting the calculated data presented in Table 2, which includes the Admiralty Coefficient (A) versus the Volumetric Froude Number (Fn_{vol}) in this case. The reason why we used the Volumetric Froude Number (Fn_{vol}) instead of the Froude Number (Fn) is not to restrict our analysis for only the mono hull type ships but to comprise all types of hull characteristics, such as catamaran or trimaran, to capture evolving naval combatant technology. Figure7 presents the Volumetric Froude Number (Fn_{vol}) versus Admiralty Coefficient (A) Curve:

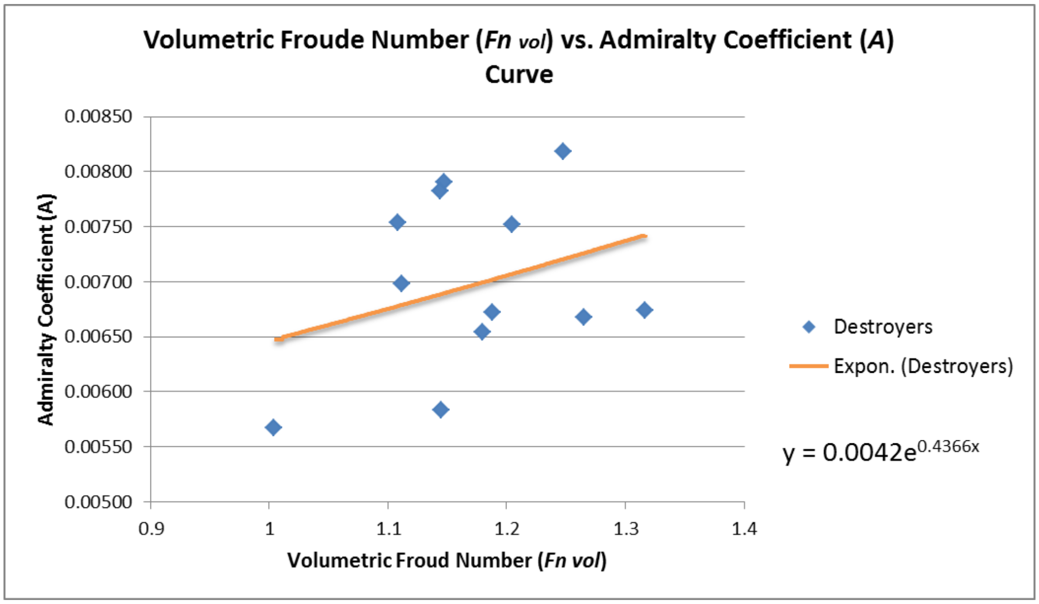

Figure 7. Volumetric Froude Number (Fn_{vol}) versus Admiralty Coefficient (A) Curve.

Assuming Equation Form

As we can observe from Figure 7 the destroyers were scattered significantly through the both sides of the exponential trend line. The corresponding equation of the trend line is presented in the lower right part of Figure 7. According to the results of the plot, and the "Best Practices Curve" approach stated in [6], we can predict the equation as a geometric equation form which is suitable for performing least squares method as

$$Y = b_0 + b_1 X^{b_2} \tag{3.8}$$

Transforming the Equation to Linear Form

We can observe from Figure 7 that the Volumetric Froude Number (Fn_{vol}) versus Admiralty Coefficient (A) Curve is a typical exponential trend line increasing at an increasing rate, which is demonstrated in Figure 5. The relationship between X and Y is a curve rather than a straight line. From this point we can create new variables to construct the linear form and express the curved function of the original variables as a linear function of our new variables. So we can start with the linearization of the predicted equation presented in Equation (3.8) by taking the logarithm of both sides:

$$Y = b_0 + b_1 X^{b_2} \tag{3.8}$$

By rearranging Equation (3.8) we get

$$Y - b_0 = b_1 X^{b_2} \tag{3.9}$$

Taking the logarithm of both sides we obtain

$$\log(Y - b_0) = \log(b_1 X^{b_2}) \tag{3.10}$$

By applying the logarithm rules we get

$$\log(Y - b_0) = \log(b_1) + \log(X^{b_2}) \tag{3.11}$$

Finally, we obtain the linear equation form derived from Equation (3.9) as

$$\log(Y - b_0) = \log(b_1) + b_2 \log(X) \tag{3.12}$$

Performing Least Squares to Fit to Data

The least squares method provides a solution to the problem of finding the best fitting straight line through a set of points, which are the data presented in Table 2 in this case. The linear least squares method can be adapted to fit the data by performing non-linear regression. To fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12) we can create a linear trend line, which will have a linear function of our new variables, by first plotting the logarithm of the Volumetric Froude Number (Fn_{vol}) versus the logarithm of the normalized Admiralty Coefficient (A). Logarithm of the parameters and the corresponding variables mentioned previously are presented in Table 3.

Name	Type	Volumetric Froude Number (Fn_{vol})	Admiralty Coefficient (A)	Normalized Admiralty Coefficient (A_n)	Log (Fn)	Log (A_n)
Forrest Sherman	DD 931	1.31680217	0.006737234	0.001163556	0.119521	-2.93421
Spruance	DD 963	1.108444775	0.007533495	0.001959817	0.044714	-2.70778
Farragut	DLG 6	1.247697878	0.008179107	0.002605429	0.096109	-2.58412
Leahy	DLG 16	1.187731447	0.006716471	0.001142793	0.074718	-2.94203
Belknap	DLG 26	1.180082538	0.006545121	0.000971443	0.071912	-3.01258
Dealey	DE 1006	1.264915822	0.006677735	0.001104057	0.102062	-2.95701
Claud Jones	DE 1033	1.003757713	0.005673678	0.0001	0.001629	-4
Bronstein	DE 1037	1.144829066	0.005835502	0.000261824	0.058741	-3.58199
Garcia	DE 1040	1.147283171	0.007908666	0.002334988	0.059671	-2.63172
Knox	DE 1052	1.112020742	0.006980271	0.001406593	0.046113	-2.85183
Brooke	DEG 1	1.14421537	0.007824414	0.002250737	0.058508	-2.64768
Oliver Hazard Perry	FFG 7	1.20429887	0.00751592	0.001942242	0.080734	-2.7117

Table 3. Logarithm of the Parameters and the Corresponding Variables, After [10].

The linear trend line, which has a linear function, was created by plotting the logarithm of the Volumetric Froude Number (Fn_{vol}) versus the logarithm of the normalized Admiralty Coefficient (A_n) presented in Figure 8.

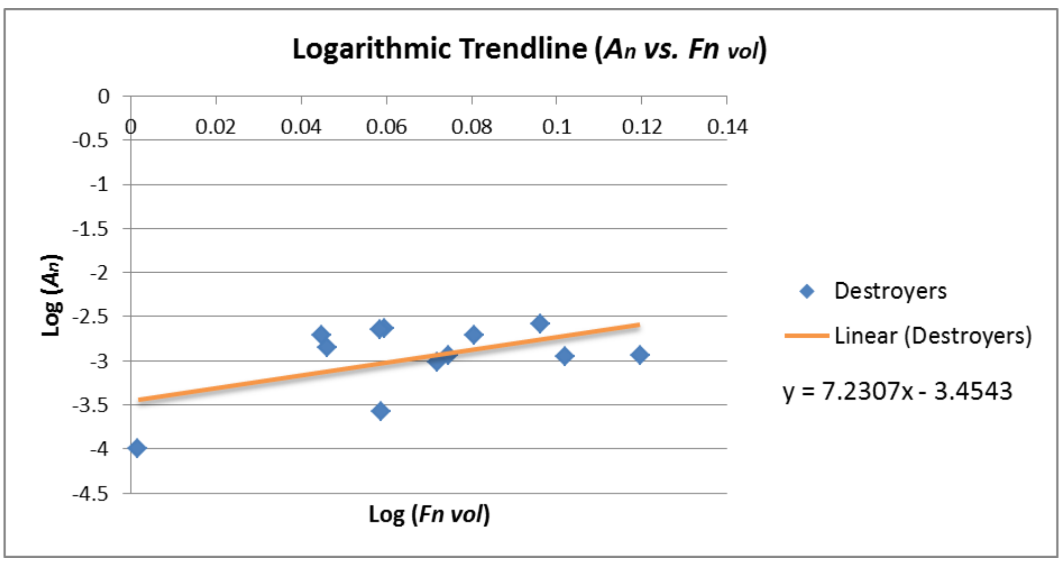

Figure 8. Logarithmic Trend Line of (A_n) versus (Fn_{vol}).

The best fitting straight line equation, as presented in the right lower section of Figure 8 through the data presented in Table 2, is as

$$Y = 7.2307X - 3.4543 \tag{3.13}$$

From this point, the linear least squares method can be adapted to fit the data by performing non-linear regression. To fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12), we convert Equation (3.13) to Equation (3.12) by performing non-linear regression by matching the variables. Rewriting the equations to be matched:

$$\log(Y - b_0) = \log(b_1) + b_2 \log(X) \tag{3.12}$$

$$Y = 7.2307X - 3.4543 \tag{3.13}$$

To determine b_0 of the logarithmic function presented in Equation (3.12) we take the minimum value of the Admiralty coefficient data from Table 3 and find the minimum value approximately as 0.00557, which was previously used for normalization of the Admiralty coefficient presented in Table 3. So we determine the value of b_0 is 0.00557. Now we can match the following variables by pairing of the following equations as

$$\log(b_1) = -3.4543 \tag{3.14}$$

$$b_1 = 10^{-3.4543} \tag{3.15}$$

From Equation (3.15) we obtain b_1 as

$$b_1 = 0.0003513 \tag{3.16}$$

To determine b_2 we set the variables of Equation (3.12) and Equation (3.13) as following where $\log(X) \to X$:

$$b_2 \log(X) = 7.2307X \tag{3.17}$$

From Equation (3.17) we get b_2 as

$$b_2 = 7.2307 \tag{3.18}$$

So far we have determined all the variables we need to fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12). We can now build the new equation form that would fit the data in a better converged manner than as in Figure 7 by rearranging Equation (3.13) as

$$Y = 0.00557 + 0.0003513X^{7.2307} \tag{3.19}$$

where Y and X correspond to Admiralty coefficient (A) and the Volumetric Froude Number (Fn_{vol}) respectively. By rewriting Equation (3.19) we obtain the Volumetric Froude Number (Fn_{vol}) versus Admiralty Coefficient (A) "Best Practices Curve" as

$$A = 0.00557 + 0.0003513(Fn_{vol})^{7.2307} \tag{3.20}$$

According to Equation (3.20), the new Admiralty coefficient (A)* and the Volumetric Froude Number (Fn_{vol})* values are calculated and tabulated in Table 4.

Name	Type	Volumetric Froude Number (Fn_{vol})	Admiralty Coefficient (A)	(Fn_{vol})*	(A)*
Forrest Sherman	DD 931	1.31680217	0.006737234	0.008139776	1.31680217
Spruance	DD 963	1.108444775	0.007533495	0.006309592	1.108444775
Farragut	DLG 6	1.247697878	0.008179107	0.00731027	1.247697878
Leahy	DLG 16	1.187731447	0.006716471	0.006788831	1.187731447
Belknap	DLG 26	1.180082538	0.006545121	0.006733202	1.180082538
Dealey	DE 1006	1.264915822	0.006677735	0.007491565	1.264915822
Claud Jones	DE 1033	1.003757713	0.005673678	0.005930958	1.003757713
Bronstein	DE 1037	1.144829066	0.005835502	0.006504145	1.144829066
Garcia	DE 1040	1.147283171	0.007908666	0.006518721	1.147283171
Knox	DE 1052	1.112020742	0.006980271	0.006327019	1.112020742
Brooke	DEG 1	1.14421537	0.007824414	0.00650053	1.14421537
Oliver Hazard Perry	FFG 7	1.20429887	0.00751592	0.006917235	1.20429887

Table 4. The New Admiralty Coefficient and the Volumetric Froude Number Values.

The Admiralty Coefficient (A) “Best Practices Curve,” presented in Figure 9, was created by plotting the new Volumetric Froude Number (Fn_{vol})* versus the Admiralty Coefficient (A)* values from Table 4.

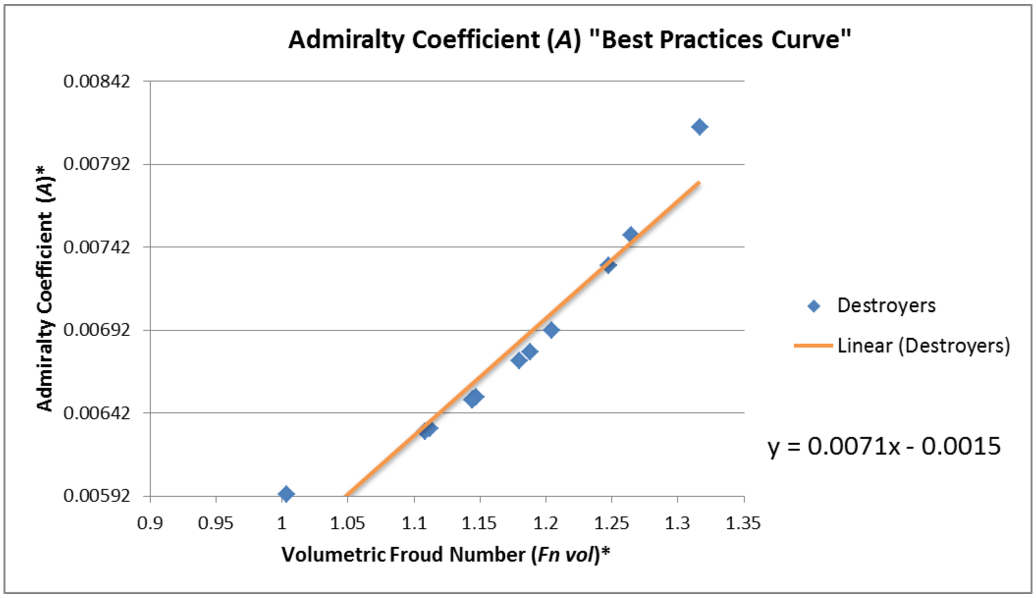

Figure 9. Admiralty Coefficient (A) “Best Practices Curve.”

As we can observe from Figure 9, destroyers from the background data are well fitted to the trend line, except for a couple deviations relative to the first curve presented in Figure 7. By implementing the Admiralty Coefficient “Best Practices Curve” approach we came up with a prediction curve, which is a linear trend line in this case, that would be used to determine the appropriate propulsion plant characteristics needed to identify the main engine selection criteria. Any point on this curve obtained by plugging in the data of a desired naval combatant will give an Admiralty coefficient prediction, which will then provide a prediction of how much power might be needed to move a given weight of ship.

D. LIFT TO DRAG RATIO (L/D) “BEST PRACTICES CURVE” APPROACH

In this approach, our analysis is based on the resistance of a ship, which is one of the parameters of primary importance in predicting propulsion power. Lift to drag ratio (L/D) curve provides a ship resistance prediction formula that we will create from the data representing a handful of widely different ship types in Table 1. We use an approach similar to the one we established in the Admiralty Coefficient “Best Practices Curve” approach described in the previous section. Our goal in this approach is to determine the required propulsion power according to the given ship speed and the resistance.

Calculations of the Parameters

As we went did in the first approach, the first step for the Lift to Drag Ratio (L/D) “Best Practices Curve” approach is to calculate the necessary parameters to create a parametric curve. From the background data representing various navy ship types in Table 1,we already calculated the ship drag (D), lift to drag ratio (L/D), Froude number (Fn), volumetric Froude number (Fn_{vol}), and the effective horsepower (EHP) of the each given ship in Table 2 that we will use for this approach. So we will use the same data presented in Table 2 in this approach.

Establishing the Volumetric Froude Number (Fn_{vol}) versus Lift to Drag Ratio (L/D) Curve

To establish an optimum equation form as we established in the first approach, we create a scatter diagram by plotting the calculated data presented in Table 2, which includes the Lift to Drag Ratio (L/D) versus the Volumetric Froude Number (Fn_{vol}) in this case. Figure10 presents the Volumetric Froude Number (Fn_{vol}) versus Lift to Drag Ratio (L/D) Curve:

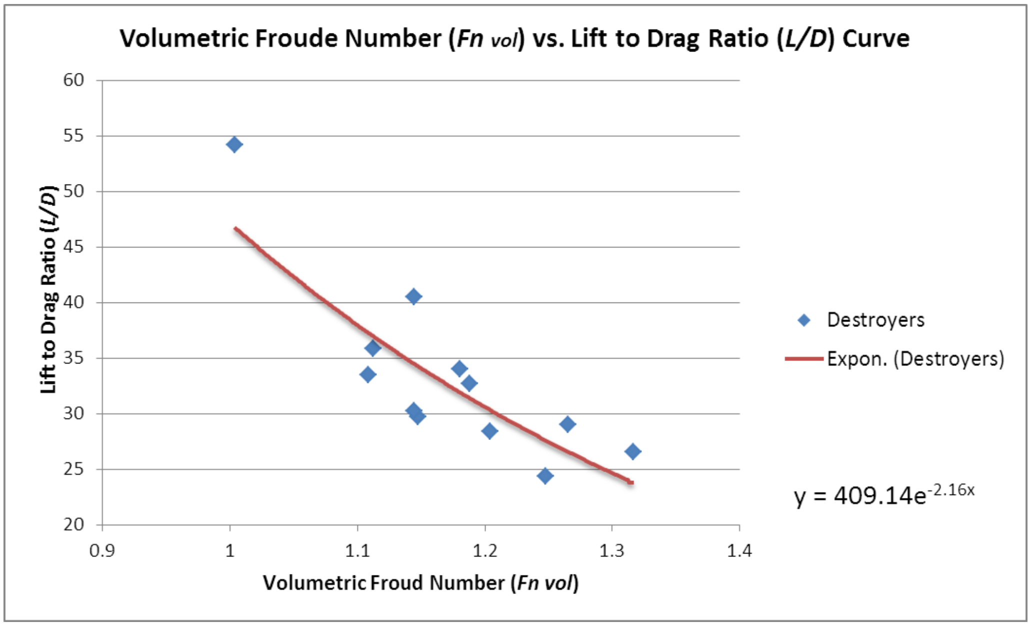

Figure 10. Volumetric Froude Number (Fn_{vol}) versus Lift to Drag Ratio (L/D) Curve.

Assuming Equation Form

As we can observe from Figure 10, the destroyers were scattered along the both sides of the exponential trend line. The corresponding equation of the trend line is presented in the lower right part of Figure 10. According to the results of the plot, the "Best Practices Curve" approach stated in [6], and the results of the Admiralty Coefficient "Best Practices Curve" approach we established previously, we can predict the equation as a geometric equation form which is suitable for performing least squares method as

$$Y = b_0 + b_1 X^{b_2} \tag{3.21}$$

Transforming the Equation to Linear Form

We can observe from Figure 10 that the Volumetric Froude Number (Fn_{vol}) versus Lift to Drag Ratio (L/D) Curve is a typical exponential trend line decreasing at a decreasing rate which is demonstrated in Figure 4. The relationship between X and Y is a curve rather than a straight line as we came up with in the first approach. From this point we can create new variables to construct the linear form to express the curved function of the original variables as a linear function of our new variables. The linearization of the predicted equation presented in Equation (3.21) has been already done in the first approach and presented in Equation (3.12).

Performing Least Squares to Fit to Data

To provide a solution to the problem of finding the best fitting straight line through the set of points presented in Figure 10, we will again use the data presented in Table 2. To fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12) we can create a linear trend line which will have a linear function of our new variables by first plotting the logarithm of the Volumetric Froude Number (Fn_{vol}) versus the logarithm of the normalized Lift to Drag Ratio $(L/D)_n$. The logarithm of the parameters and the corresponding variables mentioned previously are presented in Table 5.

Name	Type	Volumetric Froude Number (Fn_{vol})	Lift/Drag Ratio (L/D)	Normalized Lift/Drag Ratio $(L/D)_n$	Log (Fn_{vol})	Log $(L/D)_n$
Forrest Sherman	DD 931	1.31680217	26.52549704	2.188907768	0.119520534	0.340227463
Spruance	DD 963	1.108444775	33.47816357	9.141574294	0.04471406	0.961020993
Farragut	DLG 6	1.247697878	24.33668927	1E-04	0.096109436	0.5
Leahy	DLG 16	1.187731447	32.70458066	8.367991389	0.074718255	0.922621225
Belknap	DLG 26	1.180082538	33.99725183	9.660662562	0.071912384	0.985006913
Dealey	DE 1006	1.264915822	29.00239062	4.665801349	0.102061625	0.668926244
Claud Jones	DE 1033	1.003757713	54.20805031	29.87146104	0.001628895	1.475256465
Bronstein	DE 1037	1.144829066	40.51601751	16.17942823	0.058740647	1.20896317
Garcia	DE 1040	1.147283171	29.76745863	5.43086936	0.059670623	0.734869356
Knox	DE 1052	1.112020742	35.89948094	11.56289167	0.046112888	1.063066457
Brooke	DEG 1	1.14421537	30.24954419	5.912954915	0.058507777	0.771804568
Oliver Hazard Perry	FFG 7	1.20429887	28.42729586	4.090706588	0.080734279	0.61179833

Table 5. Logarithm of the Parameters and the Corresponding Variables, After [10].

The linear trend line, which has a linear function, was created by plotting the logarithm of the Volumetric Froude Number (Fn_{vol}) versus the logarithm of the normalized Lift to Drag Ratio $(L/D)_n$ presented in Figure 11.

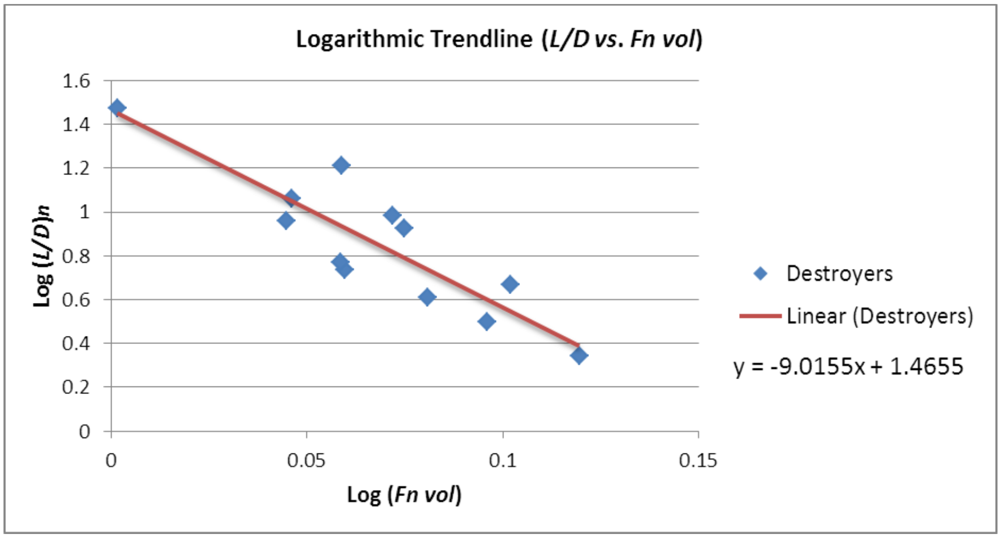

Figure 11. Logarithmic Trend Line of $(L/D)_n$ versus (Fn_{vol}).

The best fitting straight line equation as presented in the lower right section of Figure 11 through the data presented in Table 2 is as

$$Y = -9.0155X + 1.4655 \tag{3.22}$$

From this point, the linear least squares method can be adapted to fit the data by performing non-linear regression. To fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12), we convert Equation (3.22) to Equation (3.12) by performing non-linear regression by matching the variables as we established in the first approach. Rewriting the equations to be matched:

$$\log(Y - b_0) = \log(b_1) + b_2 \log(X) \tag{3.12}$$

$$Y = -9.0155X + 1.4655 \tag{3.22}$$

To determine b_0 of the logarithmic function presented in Equation (3.12), we take the minimum value of the Lift to Drag Ratio data from Table 5 and find the minimum value approximately as 24.34, which was previously used for normalization of the Lift to Drag Ratio presented in Table 5. So we determine the value of b_0 as is 24.34. Now we can match the following variables by pairing of the following equations as

$$\log(b_1) = 1.4655 \tag{3.23}$$

$$b_1 = 10^{1.4655} \tag{3.24}$$

From Equation (3.24) we obtain b_1 as

$$b_1 = 29.2 \tag{3.25}$$

To determine b_2 we set the variables of Equation (3.12) and Equation (3.22) as following where $\log(X) \to X$:

$$b_2 \log(X) = -9.0155X \tag{3.26}$$

From Equation (3.26) we get b_2 as

$$b_2 = -9.0155 \tag{3.27}$$

So far we have determined all the variables we need to fit the data in Table 2 to the curved function of the original variables of the linearized function derived in Equation (3.12). We can now build the new equation form that would fit the data in a better converged manner than as in Figure 10, by rearranging the Equation (3.22) as

$$Y = 24.34 + 29.2X^{-9.0155} \tag{3.28}$$

where Y and X correspond to Lift to Drag Ratio (L/D) and the Volumetric Froude Number (Fn_{vol}) respectively. By rewriting Equation (3.28) we obtain the Volumetric Froude Number (Fn_{vol}) versus Lift to Drag Ratio (L/D) “Best Practices Curve” as

$$\frac{L}{D} = 24.34 + 29.2(Fn_{vol})^{-9.0155} \tag{3.29}$$

According to Equation (3.29), the new Lift to Drag Ratio $(L/D)^*$ and the Volumetric Froude Number $(Fn_{vol})^*$ values are calculated and tabulated in Table 6.

Name	Type	Volumetric Froude Number (Fn_{vol})	Lift/Drag Ratio (L/D)	$(Fn_{vol})^*$	(L/D)*
Forrest Sherman	DD 931	1.31680217	26.52549704	1.31680217	26.79048262
Spruance	DD 963	1.108444775	33.47816357	1.108444775	35.8880827
Farragut	DLG 6	1.247697878	24.33668927	1.247697878	28.32062715
Leahy	DLG 16	1.187731447	32.70458066	1.187731447	30.54114852
Belknap	DLG 26	1.180082538	33.99725183	1.180082538	30.91241493
Dealey	DE 1006	1.264915822	29.00239062	1.264915822	27.85869647
Claud Jones	DE 1033	1.003757713	54.20805031	1.003757713	52.54177023
Bronstein	DE 1037	1.144829066	40.51601751	1.144829066	32.97516427
Garcia	DE 1040	1.147283171	29.76745863	1.147283171	32.81033955
Knox	DE 1052	1.112020742	35.89948094	1.112020742	35.55812916
Brooke	DEG 1	1.14421537	30.24954419	1.14421537	33.0169368
Oliver Hazard Perry	FFG 7	1.20429887	28.42729586	1.20429887	29.81429151

Table 6. The New Lift to Drag Ratio and the Volumetric Froude Number Values.

The Lift to Drag Ratio (L/D) "Best Practices Curve," presented in Figure 12, was created by plotting the new Volumetric Froude Number (Fn_{vol})* versus the Lift to Drag Ratio (L/D)* values from Table 6.

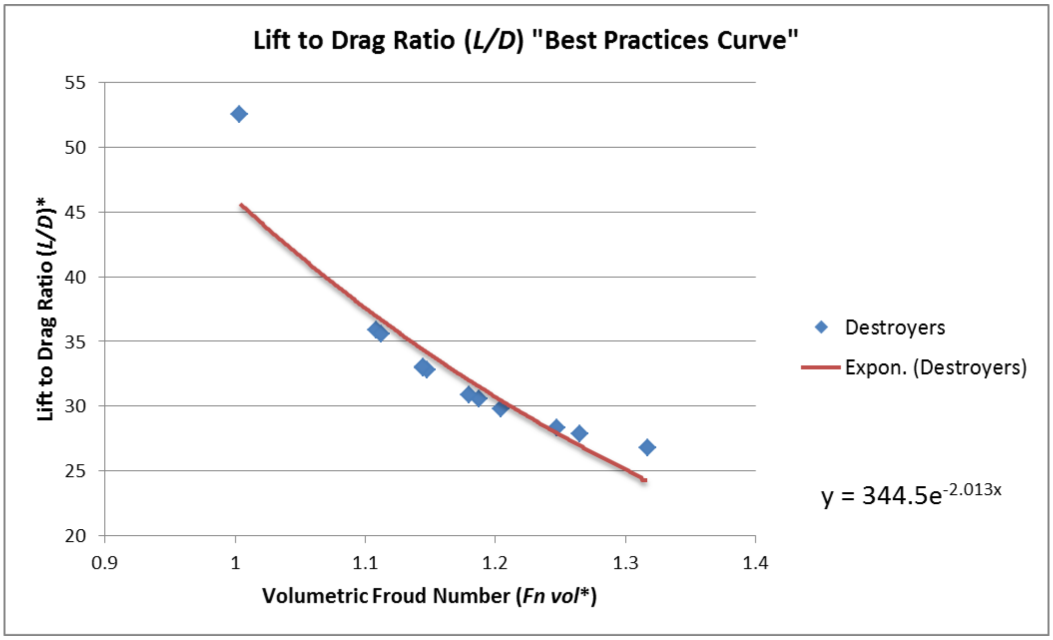

Figure 12. Lift to Drag Ratio (L/D) "Best Practices Curve."

As we can observe from Figure 12, destroyers from the background data are well fitted to the exponential trend line, except for a couple deviations relative to the first curve presented in Figure 10. As expected due to the results of the first approach, the convergence after regression analysis gets better as we can observe from comparison between Figure 10 and Figure 12. By implementing the Lift to Drag Ratio “Best Practices Curve” approach, we came up with a prediction curve in a similar way to the one we established in the first approach, which is an exponential trend line in this case, that would be used to determine the appropriate propulsion plant characteristics and identify the main engine selection criteria. Any point on this curve obtained by plugging in the data of a desired naval combatant will give a Lift to Drag Ratio prediction, which will then provide a prediction of how much power might be needed to move a given weight of ship.

E. ASSESSMENT OF THE PARAMETRIC METHOD

In this chapter we developed a mathematical model with respect to the data and corresponding criteria presented in Chapter II. To characterize the design space we established the parametric method including two different approaches to predict the propulsion plant characteristics. The first approach was established by the Admiralty Coefficient “Best Practices Curve” [6], including Admiralty coefficient versus volumetric Froude number, and the second approach was based on the “Lift to Drag Ratio (L/D) Best Practices Curve” [6], including lift to drag ratio versus volumetric Froude number. The scattered data that we were trying to analyze in the beginning was converged reasonably well after the regression analysis to create a prediction curve for both approaches. We created two prediction curves, presented in Figure 9 and Figure 12, for the Admiralty Coefficient “Best Practices Curve” approach and “Lift to Drag Ratio (L/D) Best Practices Curve” approach, respectively. These approaches would be used to determine the appropriate propulsion plant characteristics needed to identify the main engine selection criteria. We will use the results of these two parametric methods to establish our main engine selection algorithm in Chapter V.

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IV. MULTICRITERION DESIGN OPTIMIZATION

Any decision-making process requires a great amount of data collection, variable interpolation, output calculation, information acquisition, and logical processing of that information. If we look at the big picture from the information acquisition side, the more information we have and the more accurate the information is, the more likely our decision is to be correct.

The propulsion system characteristics that we want to determine in this thesis interact with many other aspects of the warship design. The decision process requires compromise with each and every piece of the design puzzle, and it needs reasonable tradeoff analysis to balance the overall demands.

Some particular specifications or even brief multiple characteristics of any propulsion system do not provide adequate decision criteria as a whole. This approach solely does not take into account operational aspects and other features of the ship design process. To undertake an optimization of a main propulsion fit, a great number of interactions within the ship design must be tested. The operational requirements or the general purposes of a designed warship interact significantly with main propulsion system options as well as their general characteristics.

The main purpose of the multicriterion design optimization is to provide the decision maker with an understanding of the effects and interactions of choosing the optimal propulsion system with respect to the analytical results of the mathematical model.

A. MAIN PROPULSION SYSTEM OPTIONS

In this section we will describe the major propulsion system options with their existing advantages and disadvantages. We will also focus on how these features and their contributions interact with the main engine selection process. After analyzing each propulsion system, we will able to define their weighting factors that eventually lead the designer to decide on the optimal choice.

1. Gas Turbines

Gas turbines have a relatively high power density compared with the other propulsion plants, especially for high-speed warships. Gas turbines are desired not only for small high-speed ships but also for larger ships that need quick acceleration when the need for high speed arises. According to [13], currently the majority of new warships worldwide in the 2,000–20,000 tons displacement range use gas turbines as whole or part of their overall propulsion power. On the other hand, gas turbines are not as efficient as the diesel engines or the other propulsion plants when cruising at lower speeds. Their maximum efficiency occurs at relatively high speeds. Most gas turbines are designed to operate inside a module that provides compactness and controllability. The modular design of a gas turbine offers several benefits like fire-detection and fire-fighting systems, engine control and surveillance system, noise reduction, shock absorption, and easy mounting and maintenance characteristics. However, the space requirements of the intake and exhaust ducts might be significant in a ship design.

From the operator's point of view, the preparation and start sequence of a gas turbine is relatively fast, so it will not take long to start and bring on line another engine if an emergency arises. This ability brings remarkable flexibility during any ship operating conditions.

Marine gas turbine power plants are designed so their parts that need frequent maintenance or repair can be easily removed and replaced. If the spare part is available at the time a failure occurs, the ship can quickly be made fully operational. Furthermore, most of the major component changes can be made while the ship is cruising. This maintenance flexibility allows continuous operation for those vessels equipped with gas turbine power plants.

2. Diesel Engines

Diesel engines are used widely as part of the propulsion system or as power electrical generators in naval applications. Although diesel engines provide superior efficiency compared to steam engines, they generally require somewhat higher quality, and hence, more expensive fuel. Typical marine diesel engines have high numbers of cylinders, which make vibration levels relatively high due to numerous rotating and reciprocating parts, even though they are mounted inside a capsule. At higher frequencies, high numbers of cylinders together with high rotational speeds create a significant proportion of the ship's noise output.

Compared with a gas turbine, diesel engines have relatively smaller air intake and exhaust ducts which are generally located upper deck of the ship. This physical reduction in ducting system and relatively lower exhaust temperatures, make the diesel less of an infrared signature (IR) source than the gas turbine.

For a warship to achieve a top speed of 30 knots, it would require multiple engines if the propulsion plant is restricted to diesel engines instead of a gas turbine. Thus, the power to weight and power to space ratios of diesel engines are pretty high compared to gas turbine engines. However, the high-speed diesel engines can be a very attractive alternative where the maximum power demands are modest or for cruise power in larger warships. As a consequence diesel engines form at least part of the propulsion systems of many newer warships today. Furthermore, diesel engines have a relatively broad speed envelope without losing effective power with respect to their efficiency in comparison to a gas turbine.

From the maintenance point of view, even though diesel engines have numerous rotating and reciprocating parts, typical engine components are modest in size and weight. These characteristics make for easier repair and replacement most of the time. On the other hand, they require relatively frequent and diverse engine maintenance compared to a gas turbine. For instance, engine oil replacement is one of the common and periodic maintenance issues for all types of diesel engines, which require continuous lubrication oil replenishment. Although major overhauls are often held ashore, diesels are typically maintained on board the warship. The diesel engine fuel system in a naval combatant is similar to a gas turbine system.

3. Oil-Fired Steam Turbines

Oil-fired steam turbines have been used for more than a century in the naval ship industry for both propulsion plants and other applications. Steam propulsion systems are not a modular or compact system like a gas turbine or diesel engine. For the system to work, steam turbines need a variety of auxiliary machines such as air blowers, lubricating oil systems, feed systems, and enormous pipework with numerous valves, which contribute to the congestion in machinery spaces. Also the maintenance load of such a complex system is relatively high compared with other marine propulsion plant options. As a result, the technically advanced naval ships today with oil-fired steam systems require high levels of manning on board in comparison to gas turbine and diesel powered ships proposed for the future.

Oil-fired steam turbines have the greatest potential to burn the widest range of fuels compared with other types of hydrocarbon-burning marine propulsion plants. This provides oil-fired turbines with the ability to burn poor-quality fuel, which tends to be the least expensive among the other marine fuel types. However, they require more space for fuel storage as well as the machinery needed to deal with high specific fuel consumption rates. The weight of a typical steam system is also greater than the weight of a comparable gas turbine and diesel engine.

Compared with other types of hydrocarbon-burning marine propulsion plants, oil-fired steam engines require greater air quantities to provide ideal burning which corresponds to larger air intake ducts for the ship. The torque versus speed characteristics of the steam turbine is similar to the characteristics of the marine gas turbine that runs a free power turbine. Compared with other marine propulsion plant options used in warships, the oil-fired steam system has the lowest efficiency. Besides, the ability to bring a steam system on line quickly is restricted due to several preparation procedures, while it takes a couple minutes for a gas turbine.

In a steam system, the exhaust temperatures are generally lower and the exhaust gas flow is far less than in similar power gas turbines or diesel engines. Consequently, the IR signature of a steam system is significantly lower than that of the other oil-burning prime movers. Furthermore, oil-fired steam systems have rotating mechanical components rather than reciprocating equipment. The inherent noise level of rotating components is much lower than reciprocating equipment and so the underwater noise signature of oil-fired steam ships would be relatively low.

Although oil-fired steam turbines have superiorities compared to the other marine propulsion plants, the gas turbine and diesel engines in naval designs have dominated the markets. In respect to overall operation, oil-fired steam systems compare unfavorably with the gas turbine and diesel power propulsion arrangements currently at sea and those proposed for the future.

4. Marine Nuclear Plant

Nuclear plant for naval use has been in progress for almost a century. The general concept for a marine nuclear propulsion plant depends on exploiting a chain reaction in a fission process as a source of power. The critical mass of the types of fissionable materials can produce energy equivalent to several million times its weight of the fuel, which makes nuclear plants compact power sources. However, the heat created in the fission process must be removed to prevent overheating of the corresponding structure and the fuel requires systematic and circumspect coolant control.

Marine nuclear plants have fuel elements surrounded by cladding, which both contains the fuel and keeps the fission particles inside the chamber. Moreover, shielding must be used to protect personnel and equipment from radiation. In case of a malfunction of the reactor or accident, a containment vessel designed into the ship prevents the uncontrolled release of radioactivity. Compared with the other marine propulsion systems, safety regulations are much more rigorous due to the catastrophic consequences that might emerge by a failure or an enemy attack.

Refueling is another important aspect that needs consideration for a marine nuclear plant. Fuel rods must be replaced periodically with respect to the maintenance schedule of the warship. To test and set the nuclear plant, completion of the refueling operation requires considerable time and resources using special facilities ashore.

Moreover, warships designed with nuclear propulsion plants need highly trained crew to respond to emergency situations or when the ship suffers action damage.

Compared with the other propulsion plant choices, marine nuclear plants are larger in size and weight. According to [13], studies in the past have suggested that a nuclear plant will be a reasonable choice unless the ship displacement is greater than 8000 tons, which can be confirmed by examining nuclear-powered warships existing today.

5. Combined Systems

Possibly an optimum propulsion system for many warships today would be a combined system consisting of multiple engine arrangements. For instance, a combined nuclear and gas (CONAG) system drives nuclear power to provide the cruise mode and gas turbines to deliver high speed and rapid acceleration. On the other hand, a combined nuclear and steam (CONAS) system offers the steam from the nuclear plant being superheated in an oil-fired steam system, which produces more efficiency.

A combined diesel and diesel (CODAD) and a combined gas and gas (COGAG) system offer all diesel engines and all gas turbines for propulsion, respectively. Diesel engines can be brought on line individually or simultaneously for a CODAD system, whereas gas turbines do the same job for a COGAG system.

There are several other combined marine propulsion systems used for a variety of applications for state-of-the-art warships. One of them is the combined diesel and gas (CODAG) system, which is highly preferred for modern frigates and corvettes. Gas turbines provide high speed and support boost features while diesel engines are used for cruise speed that prevents excessive fuel consumption. One of the advantages of a CODAG system is the ability to bring both gas turbine and diesel engine in line simultaneously to get maximum power and speed. However, a combined diesel or gas (CODOG) system is similar to a CODAG system except for its ability to engage both gas turbine and diesel engines simultaneously. The temptation of a CODAG system over a CODOG is that for given diesels and gas turbines, a higher power is available for propulsion.

It is possible to add more combinations that have been used for naval propulsion plant applications. The systems mentioned previously are the most common among the current naval propulsion plant options.

B. CONSTRAINTS TO CONSIDER WHEN DECIDING ON A PROPULSION SYSTEM

In the early stages of a ship design process, it is desirable to place as few rigid constraints on the design as possible to prevent losing necessary benefits of each characteristic of the corresponding requirement. However, there will be constraints which narrow the choice and restrict the ship builder to specific propulsion arrangements. In this section, we will examine the most common constraints that interact with the design process in a disciplined manner.

1. Technical Aspects Affecting Selection of a Propulsion System

Although there are numerous characteristics incorporating into ship power assessment continuum, the following technical aspects are predominant essential considerations affecting the selection process of a propulsion system.

Weight

In most cases, it is desirable to have the lightest possible propulsion plant to reduce the overall weight of the ship which needs less power for a given speed. The lighter the ship, the cheaper the overall operation costs would be as another consequence of this type of constraint. To decide the optimal weight of the propulsion system, several aspects of the system must be considered, such as ducting, service systems, auxiliary equipment, noise reduction and infrared suppression measures, and the fuel system(s) with its threshold storage requirements.

Space

In the early ship design process, defining the space that might be occupied by a candidate propulsion plant is difficult unless all aforementioned aspects of the propulsion package are considered. Generally, the space necessary for a machinery package can be specified as a total volume or a deck area occupied. Also the adequate space for system's maintenance should be counted within the propulsion system space demand. The length of the compartment and the effective height are two major constraints that vary significantly according to the propulsion plant type. The location of the dedicated machinery space is also important and is generally located low in the warship and just aft of amidships.

Noise

It is difficult to detect a warship which has a signature of appropriate magnitude and form merging easily with the background noise. The noise signature of a warship might provide the possibility of detection and classification by an enemy sensor system. Generally the dominant noise signature of a warship is due to machinery noise at low ship speeds and due to the hydrodynamic and propeller noise at higher speeds. So the noise-reduction measures should be assessed at the early design stage as much as possible to prevent high cost penalties further in the process. Different types of propulsion plants have different noise characteristics, as expected. Continuous flow devices such as gas turbines and steam turbines often produce lighter noise signatures whereas reciprocating engines, like diesel machinery, produce strong harmonic noise related to their operating frequency.

Infrared (IR) Signature

The main and auxiliary machinery compartments, the funnel, and the exhaust plume of a warship are typical hot bodies that have temperatures significantly above ambient temperature. These previously mentioned sources produce higher infrared radiation that might be detected by the IR seekers of enemy threats such as missiles. So it is an important countermeasure to IR seekers to suppress the IR signature of the ship.

Compared with the other propulsion plant options, the exhaust temperature of a gas turbine is relatively higher, which eventually produces higher IR signatures. So the IR suppression would be a challenge amongst the propulsion plant options. Consequently, by reducing the source level and restricting the radiation of the major IR sources, the appropriate design can reduce the probability of a vessel’s detection by an enemy IR seeker.

Magnetic Signature

High permeability within components, conducting materials within the ship, and stray electric fields such as electric motors are the major magnetic signature sources of a warship. The magnetic signature of a warship would activate a magnetic mine underwater by means of the changing magnitude of the ambient magnetic field. Large continuous areas of conducting material and continuous loops due to excessive pipework, such as an oil-fired steam system, increase the magnitude of magnetic signature.

Shock

The propulsion plant components of a warship can be subject to an enemy attack which would result in various shock waves. To protect equipment from shock forces, components must be strong enough to withstand the specific shock loads, and the mountings should be designed to protect the equipment. Generally, propulsion plant types having a modular case could be more durable compared to the open systems. This is because they have multiple flexible foundations both inside and outside of the module, like gas turbines and diesel machinery. The systems with multifarious components scattered in the machinery room along with extensive pipework are relatively vulnerable to shock forces. Furthermore, it is hard to localize and suppress any failure due to a shock wave or a fire for an open system, whereas it can be achieved in a few minutes for a modular system.

Component Efficiencies

According to [13], a typical marine gas turbine has a peak thermal efficiency of about 35%, whereas the usable efficiency of a current gas turbine remains about 20% to 25%. On the other hand, the highest thermal efficiencies can be achieved in the cruise speed range by taking advantage of the logistic support and economy of operation.

Compared with the gas turbine, the diesel engine has a higher thermal efficiency, and its efficiency is considerably constant over the power range. According to [13], low speed diesels have more than 45% thermal efficiency, whereas high speed diesels have 40%. Generally, the high and medium speed diesel engines offer a very competitive alternative against gas turbines in terms of power, efficiency, and maintenance, even with added weight and space penalties.

Fuel Consumption

Fuel consumption of a propulsion system is highly related with the component efficiencies discussed previously. The higher the component efficiencies for a broad speed range, the lower the fuel consumption of a propulsion unit. Fuel consumption has several effects on the ship design process. Selecting a propulsion system having low specific fuel consumption would decrease the demand of fuel stowage and so the weight and space occupied by it. Thus, the ship would need less fuel replenishment at sea which would increase its operational endurance in a naval task. Furthermore, lower fuel consumption will eventually provide lower through-life costs by the quantity of fuel consumed.

2. Non-technical Aspects Affecting the Decision Process

As mentioned at the end of Chapter II, several other aspects must be considered in selecting a propulsion system as well. Although some of these factors are not easily quantifiable, they are important.

Reliability

Reliability is defined in [13] as "the probability of a unit not being out of action with a non-repairable at sea failure." As stated in the previous definition, reliability of a propulsion plant depends on its continuous operation without the failure that could not be repaired at the time of necessity. The availability of spare parts and necessary tools, availability of an expert crew to undertake the repair, and operability of the warship during the repair are key requirements for a propulsion plant to be considered reliable. Many warships have been designed to accommodate multiple parallel systems to improve the overall system reliability. From this point of view, combined systems with multiple engine types are relatively more reliable because they permit switching between the modes in case of a failure. This ability brings flexibility during the repair process by disengaging and localizing the malfunction of a specific engine even though the overall propulsion system power decreases.

The power plant systems that have been at sea for several years provide considerable data about common failures which can be used to establish an optimal maintenance procedure. Knowing when and which part of a propulsion system needs to be replaced or serviced will increase the reliability of that particular system. By contrast, it is difficult to make an accurate assessment of a new design without any background data.

Availability

As defined in [13], availability is “the proportion of time a unit is available when taking into consideration repairable at sea failures.” Availability is also written in [13] as

$$A = \frac{MTBF(RS)}{MTBF(RS) + MTTR} \tag{4.1}$$

where $MTBF(RS)$ is the Mean Time Between Failure (Repairable at Sea) and MTTR is the Mean Time to Repair. The magnitude of MTTR is highly dependent on the availability of maintenance personnel and the supply of the correct spare parts at the instant of a failure. To get the maximum availability from a propulsion plant, the precise time dependency envelope of failure rates of the system must be obtained. This information provides the optimum maintenance schedule for keeping the propulsion plant available as much as possible.

Maintainability

Propulsion plant types vary in their maintenance demands requiring both different maintenance skills and different numbers of expert maintenance personnel. A propulsion plant may require maintenance that can either be undertaken on board or by removing equipment and maintaining it ashore. Any spontaneous failures can be overcome by adequate spare parts, material, and tools, as well as the expertise of personnel to conduct the best plan of action.

Vulnerability

The vulnerability assessment of a propulsion system to be selected for a particular warship can be established by defining the possible threats against that particular type of ship. A ship may be attacked by missiles, underwater explosives, or only modest caliber guns. Each type of threat will result in different types of effects on the propulsion system. A reasonable vulnerability assessment requires eliminating impossible threats, and focusing on the most probable ones with their side effects. However, the degree of improvement necessary for the vulnerability of the candidate propulsion system is fuzzy. It is important to consider possible damage mechanisms that might be caused by the threat envelope to determine the vulnerability reduction features necessary for the propulsion system. Eventually, this approach would at least give an idea about how vulnerable the propulsion system should be to fit the ship under consideration.

Another important vulnerability aspect of propulsion systems is the ability of some machinery or parts to be repaired rapidly. For instance, a steam system hit may take more time to repair than a turbine system due to the residual heat of the components, even if the repair itself could be done simply. As mentioned before, failure of a modular system can be localized and repaired easily rather than failure in an open system. The longer the repair time takes, the more vulnerable the ship is against later possible attacks due to its idle position caused by the failure.

Maneuverability

For a surface combatant, it is considered crucial to be able stop with a specific distance from a specified speed. The importance of this characteristic would arise for emergency operations and for operating in a joint task force. The level of maneuverability can be determined by the type of propulsion system mounted on the ship, the arrangement of the transmission, the number and type of propeller, number of shafts, and the propulsion control system. High maneuverability could allow flexibility in the propulsion plant design if the major governing factors originated from aspects other than the machinery.

Industrial Base

To keep the current propulsion plant of a warship in service throughout its lifetime, it is crucial to get design, production, and hardware support from the organization of the propulsion plant company without any discontinuity. It is obvious that components of a power plant need continuous maintenance, which requires replacement of the integral parts. Any lack of service from the industrial base can present serious problems to the operators and maintainers, which eventually affects the survivability of a warship. For the reasons previously mentioned, a wide and diverse industrial base has many advantages as it has the potential for spare parts and new units to be available quickly for warships. There are several propulsion plant brands worldwide that most of the naval forces have been using on their warships for decades. However, the political situation and the relationship of the foreign manufacturer with the homeland country must also be considered throughout the decision process to prevent loss of support in the case of a crisis.

Manning

Another important restriction while selecting a propulsion system is the limitation on the total number of men available on the ship or ashore along with their skill levels. A current trend in the naval industry today is to minimize the overall crew size while maintaining the operability and effectiveness of the fleet. Reducing the crew size would affect favorably the overall cost by preventing weight, space, and cost penalties in the ship design. According to [13], reduction in the crew size can be achieved by simplifying the tasks to be performed by the crew, eliminating tasks that need human involvement, and transferring some tasks that can be done by the teams of shore-based labor instead of maintaining them at sea by the ship staff. Due to sophisticated machinery controls and surveillance systems, unmanned automatic power systems have been used for years to minimize the ship’s operational crew size both in peace and in hostile environment. Consequently, it is very important to consider the aspects previously mentioned while selecting a propulsion system to optimize the manning on board.

Initial and Through-Life Costs

There are various components that contribute to the overall costs associated with surface warship propulsion. As expected, costs are one of the major driving forces in a ship design process. To undertake a meticulous comparison between propulsion system options, a wide range of characteristics has to be analyzed against a ship specification. Although these characteristics can be extended as far as possible, as listed in [13], key requirements are weapon fit, top speed, cruise speeds, endurance, ship signatures, availability, reliability, and maintainability, maneuverability, vulnerability, and support arrangements. Weight, space, and efficiency demands with dissimilarities between propulsion options can result in different ships in terms of size, weight, and power.

In a warship design process the minimum limits of the characteristics must be determined to keep all important characteristics at reasonable levels. When it comes to the tradeoff analysis, a designer should know which characteristics might be sacrificed against a demanding feature arising from the nature of the design process.

If we look at the cost picture from a broad perspective, we can define through-life costs as the costs representing all costs that occur during the life of the ship, including the concept and design phases. As listed in [13], through-life costs consist of initial costs, development costs, and design costs, costs of initial supply of spares and handbooks, fuel costs, manpower costs, maintenance and repair costs. The costs occurring over a short period early in the life of the ship are called initial costs [13], whereas other costs occur when the ship is at sea. Some propulsion systems might have a relatively low initial cost but are expensive to operate and maintain during the life of the ship and vice versa.

3. Objective Judgment Process

The objective judgment process involved in selecting a propulsion system primarily consists of two parts: weighting of the ship's expected characteristics and assigning merit numbers to the various propulsion systems under consideration.

Although the propulsion system selection process significantly depends on what tasks the ship should be required to perform and what characteristics are expected of the ship, the weighting factors can give an indication of which areas receive priority in the design. The reliability of designating weighting factors depends on reasonable discussion and agreement between the stakeholders involved in the ship design. Weighting factors help to determine what characteristics are of greatest importance at a particular design phase, and which are of modest significance that can be sacrificed.

The merit numbers created by multiplying the weighting factor with the assessment of each factor for a given propulsion system can be compared with the merit numbers of alternative propulsion system options for the type of ship being considered as exemplified in Table 7. This comparison between several propulsion system options gives a reasonable suggestion as to what further decision criteria need to be considered.

		Technical Aspects								Non-Technical Aspects								
		Weight	Space	Noise	IR Signature	Magnetic Signature	Shock	Efficiency	Fuel Consumption	Reliability	Availability	Maintainability	Vulnerability	Maneuverability	Industrial Base	Manning	Costs	Merit Number
Gas Turbine	Score	8	7	6	4	5	7	6	4	9	8	8	7	8	7	7	6	
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	Σ668
	Product	64	35	18	16	10	35	48	32	81	64	56	42	40	42	49	36	
Diesel Engine	Score	6	6	5	7	4	6	8	8	8	8	7	6	7	8	6	8	
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	Σ681
	Product	48	30	15	28	8	30	64	64	72	64	49	36	35	48	42	48	
Oil-fired Steam Turbine	Score	4	5	8	8	7	3	6	6	6	4	5	3	5	6	4	8	
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	Σ514
	Product	32	25	24	32	14	15	48	48	54	32	35	18	25	36	28	48	

Marine Nuclear Plant	Score	7	6	8	8	7	6	8	9	6	6	5	4	7	4	5	4	Σ601
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	
	Product	56	30	24	32	14	30	64	72	54	48	35	24	35	24	35	24	
CODAG	Score	7	6	7	8	7	7	8	8	9	9	8	7	8	8	7	8	Σ752
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	
	Product	56	30	21	32	14	35	64	64	81	72	56	42	40	48	49	48	
COGAG	Score	8	7	7	6	7	7	7	6	8	9	8	7	8	8	7	7	Σ718
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	
	Product	64	35	21	24	14	35	56	48	72	72	56	42	40	48	49	42	
CONAG	Score	6	6	8	7	7	6	7	7	7	8	6	5	8	5	6	6	Σ633
	Weighting factor	8	5	3	4	2	5	8	8	9	8	7	6	5	6	7	6	
	Product	48	30	24	28	14	30	56	56	63	64	42	30	40	30	42	36	

Table 7. Merit Table, After [13].

V. MAIN ENGINE SELECTION ALGORITHM

In this chapter we will establish an algorithm which can be derived by using the optimized data points from the “Best Practices Curve” [6] approaches examined in Chapter III for desired input parameters of any given ship requirements. By establishing the algorithm, we will be able to predict the optimum propulsion plant characteristics as to how much power might be needed to move a given ship via its predefined requirements.

A. ASSUMPTIONS

To provide a dependable prediction of how much power might be needed to move a given ship, we need to make few reasonable assumptions according to the values that are held to be state of the art. These assumptions are the Overall Propulsive Coefficient (OPC), weight of power, cargo carriage multiplier, and the specific fuel consumption (SFC).

The values of OPC that are held to be most current, shown in Figure 13, are taken from [13]. As can be seen from Figure 13, curves are created by plotting the dimensional ship speed values versus the corresponding OPC values. As stated in [6], the curve suggests a median OPC value of 0.6 might be for propellers, including both surface-piercing and fully submerged types, whereas a median OPC value of 0.7 might be for waterjets.

The weight of the power source that corresponds to the value of a weight quantity per horsepower, including all of its components, can be estimated according to similar ship types. As stated in [6], analysis of an existing ship design gives real-world values of this parameter near the range of 8 to 10 pounds per horsepower.

Another aspect that affects the power prediction process is the weight of cargo carrying capacity which can be denoted as cargo carriage multiplier. This parameter includes structure, crew, auxiliary systems, and other loads that can be regarded as part of the payload. As stated in [6], a reasonable estimation of this multiplier would be a value between 1 to 11 pounds per pound.

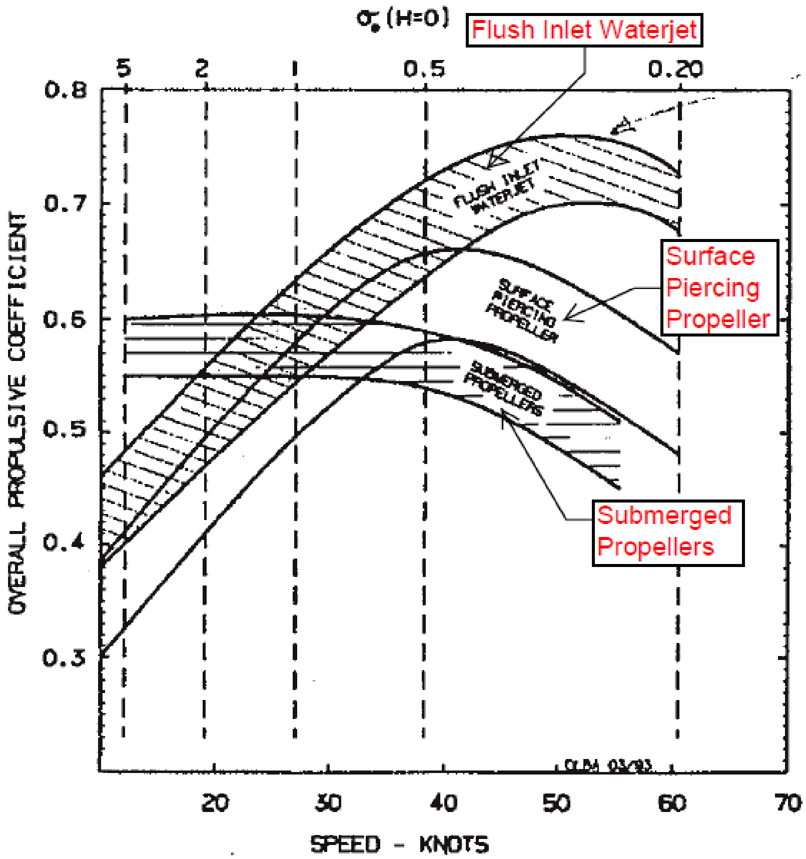

Figure 13. State-of-the-Art Performance for Waterjets and Other Propulsors, After [14].

The overall fuel consumption of the machinery is the last parameter that we assume for our selection algorithm on a specific or per-horsepower-hour basis. We will use the data from [6] as it represents the state of the art, by collecting SFC data from commercial sources such as engine catalogs. As stated in [6], Figure 14 shows the SFC values reported for a variety of modern turbines in navy services, plotted against their output power. The writer of [6] also estimated the level of SFC performance that might be attained by future larger engines, illustrated in Figure 14, by a visual extension of the line. According to the plot in Figure 14, we can estimate the approximate SFC with respect to the total power that might be produced from a typical propulsion plant.

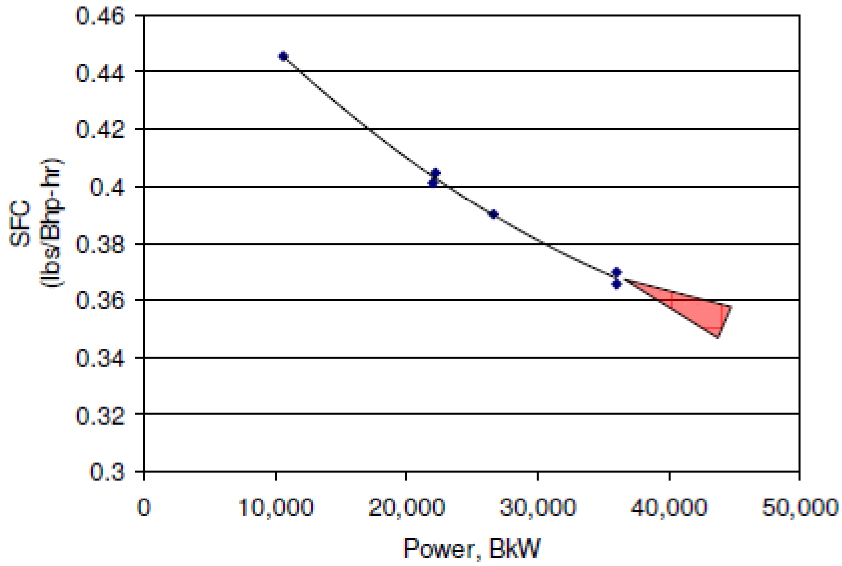

Figure 14. Propulsion GT Engines, SFC versus Power, Current and Future Engines, From [6].

B. MAIN ENGINE SELECTION ALGORITHM

While there are many formal definitions of “algorithm,” the most appropriate interpretation for our analysis could be the step-by-step procedure which comprises input variables as ship speed, range, length, displacement, payload along with the coefficients that results required weight and power estimations as final outcome such as machinery weight, SHP, EHP, and Drag which will be used in a preliminary ship design process.

To compare the results and to decide on the most realistic approach, both the Admiralty Coefficient “Best Practices Curve” and the “Lift to Drag Ratio (L/D) Best Practices Curve” [6] methods, established in Chapter III, were imbedded separately in the algorithm.

The input parameters logged into the algorithm shown in Table 8 were taken from the first ship data presented in Table 1 as an example. The other ship data in Table 1 were also logged into the algorithm respectively to determine how the results are converged to the actual data representing the background data of various navy ship types presented in Table 1.

1. Main Engine Selection Algorithm Layout

The main engine selection algorithm layout basically consists of input and output modules, which are sequentially organized within the algorithm as presented in Table 8. We have speed, endurance speed, range, length, displacement, and payload as input parameters regarded as the most definitive parameters of a given ship. After running the algorithm with these input parameters, we obtain two sets of weight and power results interrelated with respect to the Admiralty coefficient and the Lift to Drag ratio methods, respectively. We used six governing parameters presented in Table 8, along with the volumetric Froude number. The first two parameters are the Lift to Drag ratio and the Admiralty coefficient derived in Chapter III as the deterministic variables. The other four parameters were assumed with respect to the data mentioned in the previous section.

The algorithm we derived consists of the sequential procedure that starts with incorporating input parameters of consecutive ship data from Table 1 as illustrated in Table 8. Secondly, the imbedded equations provide computations of the algorithm parameters along with the assumed variables which are defined in Chapter II. After running the algorithm we obtained two sets of results which are the weight and the power solutions with respect to the Lift to Drag ratio and the Admiralty coefficient methods. The results of the both methods including weight and power estimations provide the idea of the optimum propulsion plant characteristics in a preliminary ship design process.

All the data obtained by the algorithm with respect to the input parameters of consecutive ship data from Table 1 and the corresponding error values were tabulated in Table 9 through Table 12 for comparison. To visualize the results of each run, SHP, Endurance SHP, EHP, and the Drag values are plotted against the displacement values, respectively. These plots presented in the "Analysis of the Results and Comparison" section provide a visual comparison of how the result of the two approaches previously mentioned were converged to the actual values.

ENGINE SELECTION ALGORITHM				
INPUT PARAMETERS	PARAMETER	UNIT	VALUE	NOTE
	Speed, V	knots	33	Input
	Endurance Speed, V_{en}	knots	20	Input
	Range	NM	4500	Input
	Length (LOA)	ft	418.5	Input
	Displacement, Δ	LT	4916	Input
	Displacement, Δ	lb	11011840	Input
	Payload	LT	2182	Input
CONSTANT PARAMETERS	Gravitational Accelaration, g	ft/sec^2	32.174	Constant
ALGORITHM PARAMETERS	Volumetric Froude Number, Fn_{vol}		1.31680217	Calculated
Parameter #1	Lift to Drag Ratio (L/D)*		26.78256135	Calculated
Parameter #2	Admiralty Coefficient (A)*		0.008139776	Calculated
Parameter #3	Overall Propulsive Coefficient, OPC		0.6	Assumed
Parameter #4	Specific Fuel Consumption, SFC	lbm/hp-hr	0.4	Assumed
Parameter #5	Weight of Power	lbs/hp	8	Assumed
Parameter #6	Cargo Carriage Multiplier	lbs/lb	2	Assumed
WEIGHT RESULTS	Admiralty Coefficient (A) "Best Practices Curve" Method Calculations			
	Fuel Weight	LT	756.4348266	Calculated
	Machinery Weight	LT	302.0444262	Calculated
	Displacement Minus Fuel	LT	4159.565173	Calculated
	Weight Available for Cargo & C.Carriage	LT	3857.520747	Calculated
	Cargo Carriage Weight	LT	2571.680498	Calculated
	Cargo Load	LT	1285.840249	Calculated
	"Lift to Drag Ratio (L/D) Best Practices Curve" Method Calculations			
	Fuel Weight	LT	620.6888257	Calculated
	Machinery Weight	LT	247.8410481	Calculated
	Displacement Minus Fuel	LT	4295.311174	Calculated
	Weight Available for Cargo & C.Carriage	LT	4047.470126	Calculated
	Cargo Carriage Weight	LT	2698.313417	Calculated
	Cargo Load	LT	1349.156709	Calculated
POWER RESULTS	Admiralty Coefficient (A) "Best Practices Curve" Method Calculations			
	Shaft Horsepower, SHP	hp	84572.43935	Calculated
	Shaft Horsepower, SHP (Endurance)	hp	18826.82235	Calculated
	Effective Horsepower, EHP	hp	50743.46361	Calculated
	Total Hull Resistance, Rt	lbf	501078.0436	Calculated
	Total Hull Resistance, Rt	kN	2228.906377	Calculated
	"Lift to Drag Ratio (L/D) Best Practices Curve" Method Calculations			
	Shaft Horsepower, SHP	hp	69395.49347	Calculated
	Shaft Horsepower, SHP (Endurance)	hp	15448.25522	Calculated
	Effective Horsepower, EHP	hp	41637.29608	Calculated
	Total Hull Resistance, Rt	lbf	411157.0905	Calculated
	Total Hull Resistance, Rt	kN	1828.918015	Calculated

Table 8. Engine Selection Algorithm.

2. Analysis of the Results and Comparison

SHP data obtained by the algorithm with respect to the input parameters of consecutive ship data from Table 1 and the corresponding error values were tabulated in Table 9 for comparison.

Name	Type	SHP Actual Values (hp)	SHP From Admiralty Results (hp)	SHP From (L/D) Results (hp)	Relative Error From Admiralty Results (%)	Relative Error From (L/D) Results (%)
Forrest Sherman	DD 931	70,000	84,572	69,395	20.8	0.9
Spruance	DD 963	80,000	67,003	74,714	16.2	6.6
Farragut	DLG 6	85,000	75,971	73,138	10.6	14.0
Leahy	DLG 16	85,000	85,916	91,140	1.1	7.2
Belknap	DLG 26	85,000	87,443	93,604	2.9	10.1
Dealey	DE 1006	20,000	22,437	20,848	12.2	4.2
Claud Jones	DE 1033	8,700	9,095	8,980	4.5	3.2
Bronstein	DE 1037	20,000	22,292	24,604	11.5	23.0
Garcia	DE 1040	35,000	28,849	31,794	17.6	9.2
Knox	DE 1052	35,000	31,725	35,377	9.4	1.1
Brooke	DEG 1	35,000	29,078	32,106	16.9	8.3
Oliver Hazard Perry	FFG 7	40,000	36,814	38,189	8.0	4.5

Table 9. SHP Comparison.

Figure 15 presents how the result of the ‘Admiralty’ and the ‘L/D Ratio’ methods converged to the actual values. The values that reach up to 80,000 hp show reasonable consistency, whereas it starts to deviate slightly for higher power values.

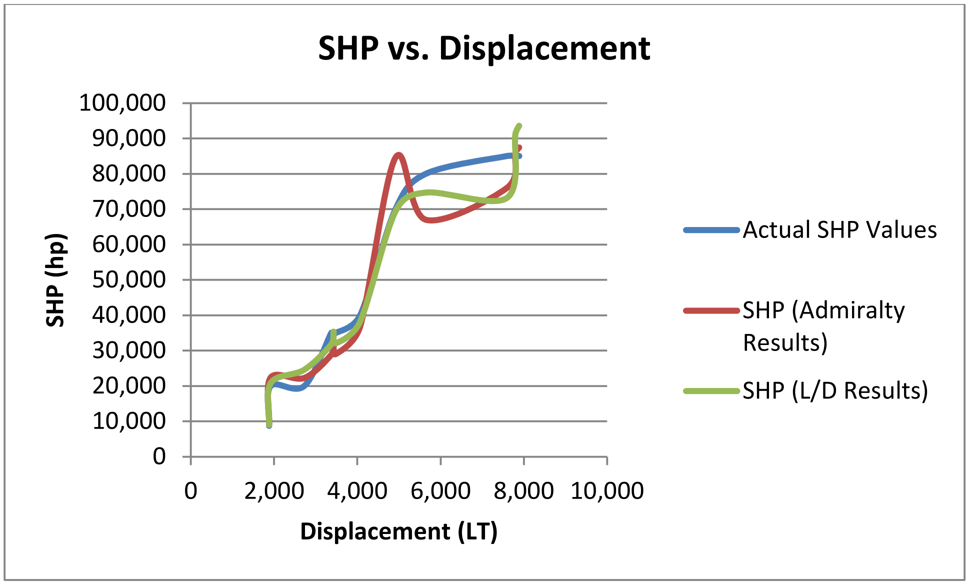

Figure 15. SHP versus Displacement.

Endurance SHP data obtained by the algorithm with respect to the input parameters of consecutive ship data from Table 1 and the corresponding error values were tabulated in Table 10 for comparison.

Name	Type	SHP(End) Actual Values (hp)	SHP(end) From Admiralty Results (hp)	SHP(end) From (L/D) Results (hp)	Relative Error From Admiralty Results (%)	Relative Error From (L/D) Results (%)
Forrest Sherman	DD 931	15,583	18,827	15,448	20.8	0.7
Spruance	DD 963	23,704	19,853	22,138	16.2	7.9
Farragut	DLG 6	20,752	18,548	17,856	10.6	15.6
Leahy	DLG 16	20,752	20,976	22,251	1.1	7.1
Belknap	DLG 26	20,752	21,348	22,852	2.9	9.8
Dealey	DE 1006	1,756	1,970	1,830	12.2	3.8
Claud Jones	DE 1033	1,513	1,581	1,561	4.5	3.1
Bronstein	DE 1037	3,840	4,281	4,725	11.5	20.7
Garcia	DE 1040	14,225	11,725	12,922	17.6	11.1
Knox	DE 1052	14,225	12,894	14,379	9.4	1.2
Brooke	DEG 1	14,225	11,819	13,049	16.9	10.0
Oliver Hazard Perry	FFG 7	13,823	12,722	13,198	8.0	4.9

Table 10. Endurance SHP Comparison.

Unless the power values exceed approximately 13,000 hp, as seen from Figure 16, endurance SHP values are almost matched up with the actual values for both methods. For higher values we observe slight deviations in endurance SHP comparison, but the endurance SHP values still stay in a reasonable prediction envelope that remains consistent even at higher values.

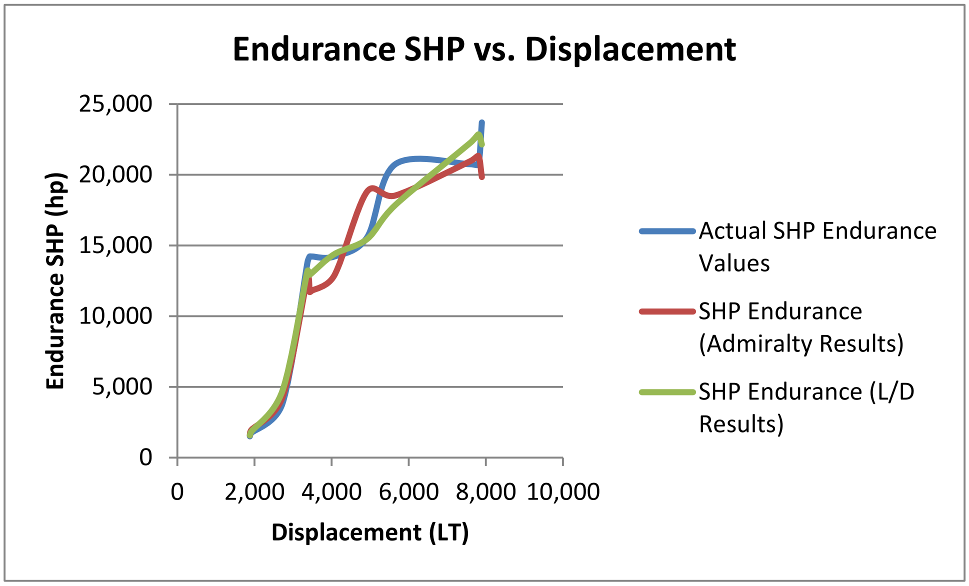

Figure 16. Endurance SHP versus Displacement.

EHP data obtained by the algorithm with respect to the input parameters of consecutive ship data from Table 1 and the corresponding error values were tabulated in Table 11 for comparison.

Name	Type	EHP Actual Values (hp)	EHP From Admiralty Results (hp)	EHP From (L/D) Results (hp)	Relative Error From Admiralty Results (%)	Relative Error From (L/D) Results (%)
Forrest Sherman	DD 931	42,000	50,743	41,637	20.8	0.9
Spruance	DD 963	48,000	40,202	44,828	16.2	6.6
Farragut	DLG 6	51,000	45,582	43,883	10.6	14.0
Leahy	DLG 16	51,000	51,549	54,684	1.1	7.2
Belknap	DLG 26	51,000	52,466	56,162	2.9	10.1
Dealey	DE 1006	12,000	13,462	12,509	12.2	4.2
Claud Jones	DE 1033	5,220	5,457	5,388	4.5	3.2
Bronstein	DE 1037	12,000	13,375	14,763	11.5	23.0
Garcia	DE 1040	21,000	17,309	19,076	17.6	9.2
Knox	DE 1052	21,000	19,035	21,226	9.4	1.1
Brooke	DEG 1	21,000	17,447	19,264	16.9	8.3
Oliver Hazard Perry	FFG 7	24,000	22,088	22,914	8.0	4.5

Table 11. EHP Comparison.

As expected, we can observe from Figure 17 that EHP values illustrate the same behavior as that in the SHP comparison due to the OPC value, which was assumed 0.6 as constant for both methods.

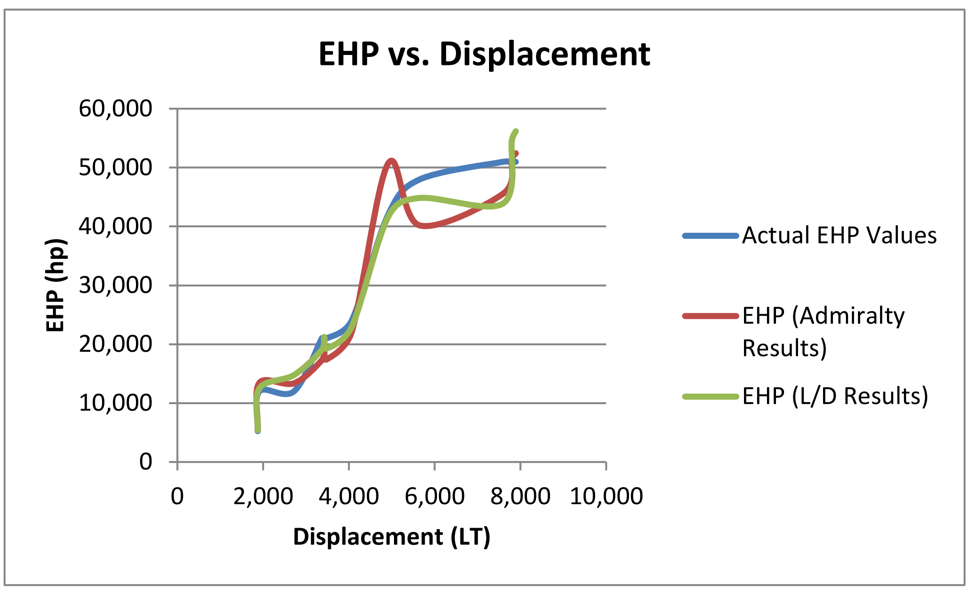

Figure 17. EHP versus Displacement.

Drag data obtained by the algorithm with respect to the input parameters of consecutive ship data from Table 1 and the corresponding error values were tabulated in Table 12 for comparison.

Name	Type	Drag Actual Values (kN)	Drag From Admiralty Results (kN)	Drag From (L/D) Results (kN)	Relative Error From Admiralty Results (%)	Relative Error From (L/D) Results (%)
Forrest Sherman	DD 931	1,847	2,229	1,829	20.7	1.0
Spruance	DD 963	2,322	1,942	2,166	16.4	6.7
Farragut	DLG 6	2,313	2,065	1,988	10.7	14.1
Leahy	DLG 16	2,313	2,335	2,477	0.9	7.1
Belknap	DLG 26	2,313	2,377	2,544	2.7	10.0
Dealey	DE 1006	645	723	672	12.0	4.1
Claud Jones	DE 1033	352	368	363	4.4	3.1
Bronstein	DE 1037	670	746	823	11.3	22.9
Garcia	DE 1040	1,129	929	1,024	17.7	9.3
Knox	DE 1052	1,129	1,022	1,140	9.5	0.9
Brooke	DEG 1	1,129	937	1,034	17.0	8.4
Oliver Hazard Perry	FFG 7	1,222	1,123	1,165	8.1	4.6

Table 12. Resistance (Drag) Comparison.

Figure 18 presents the comparison of the ship drag values with respect to both methods established in the algorithm. As observed, drag results follow a closer path according to the actual values, thus providing considerable ship resistance prediction.

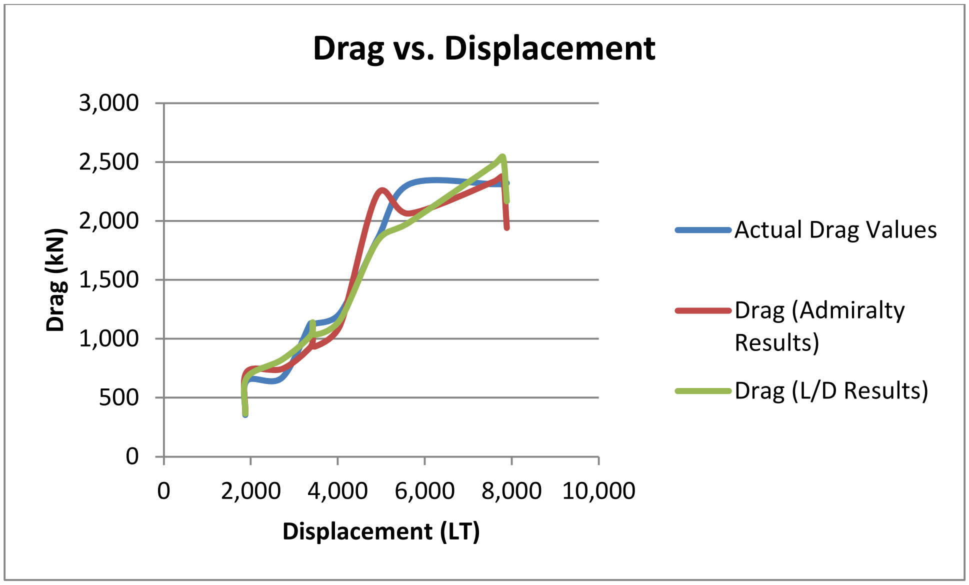

Figure 18. Drag versus Displacement.

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VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis provides a comprehensive unbiased methodology for a surface combatant main engine selection problem, including the assessment of how well each machinery option will perform in relation to each characteristic. The methodology allows the initial estimate of the power requirements to be made for a proposed naval vessel. The overall benefit of this research is that it provides a multidisciplinary design space examination which can be used by decision makers within the scope of the requirements and emerging technologies.

The major results following the established methodological framework are:

1. A baseline parametric framework was established by the data from a handful of widely different navy ship types to create desired trend lines to set a prediction concept.
2. The factors that need to be taken into consideration while selecting a main engine for a navy ship were defined to be used in the mathematical model.
3. A mathematical model was developed, which is based on two different approaches: the Admiralty Coefficient "Best Practices Curve" [6], and the "Lift to Drag Ratio (L/D) Best Practices Curve" [6], with respect to the data and corresponding criteria to predict the propulsion plant characteristics. It was established that both the Admiralty coefficient and the Lift to Drag ratio parameters provided a prediction of how much power might be needed to move a given navy ship.
4. The multicriterion design optimization revealed propulsion system options that are considered in relation to the initial ship characteristics, allowing for an assessment without disregarding the propulsion plant options. The weighting factors, along with the merit numbers derived in the optimization, give an indication of which areas to bias the design towards. This enables the designer to reach an understanding of which options have attractive features and which have aspects that are inappropriate for the particular ship design.
5. The engine selection algorithm was derived using the optimized data points from the "Best Practices Curve" [6] methods for desired input parameters of the given ship requirements. By use of this algorithm, for any desired ship with its predefined requirements, a decision maker can predict the optimum propulsion plant characteristics.

6. The methodology is adequately effective and the thesis provides a rapid tool to be utilized in making conceptual design decisions in the preliminary ship design, and assessment of alternative propulsion plant options for a surface combatant.

The results of this research and the overall study can be extended and developed in several areas, which are summarized as follows:

1. The analysis presented in this thesis is essential, but it represents only one of the initial steps that must be examined in a preliminary ship design process. Further benefits could be derived from implementing subsequent design milestones, such as propulsion system integration, which would illuminate the overall warship propulsion system selection in an extended viewpoint.
2. Incorporating transmission, shaft and propeller system assessments into the analysis would maximize the possible design options, including the overall power plant components.
3. Analyzing and incorporating emerging marine power technologies, such as electric drive propulsion or hybrid power options, together with the most current systems would provide alternative solutions to the engine selection problem.

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